Fire Development in Rooms Partially Lined with Timber

A thesis submitted in partial fulfilment
of the requirements for the
Degree of Master of Engineering in Fire Engineering
in the University of Canterbury
by H. Peel

University of Canterbury

2016

Abstract

Combustible internal linings have been identified as a major contributor in several high-profile fire events. Legislators have sought to address the risk posed by combustible linings by classifying and restricting their use in some spaces. This study compares the standard tests and classification methods for internal timber linings in the U.S.A, Canada, U.K., Europe, Australia and New Zealand. Building legislation such as the New Zealand Building Code generally assumes that all wall and ceiling surfaces in a space are lined with the products of similar reaction to fire performance and this reduces the choices available to the designer and often excludes partial combustible linings, apart from some minor concessions.

To examine the justification for this assumption a series of seven room experiments are conducted in the conditions required by ISO 9705 with different configurations of 7 mm thick plywood linings on the walls and ceiling and the remainder of the enclosure lined with non-combustible calcium silicate board. The heat release rate, gas temperatures and flame spread rates were measured. The relative performance of the lining configurations is assessed by either ranking the time-to- flashover and peak rate of heat release or using the $FIGRA_{RC}$ methodology. Flashover was achieved in 4 tests. $FIGRA_{RC}$ was found to be a better means of comparing the performance of the seven configurations as it more accurately and intuitively represented the rate of fire development than time to flashover or peak heat release rate measurements.

The feasibility of using a modified version of the B-RISK zone model to simulate fire growth in the same enclosures is examined. The rate of heat release and time to flashover from the experiments are compared with simulations using a modified version of B-RISK. The B-RISK flame spread algorithms have been altered to allow for modelling of ceilings and walls which are only partially lined with combustible linings. Model input data for the plywood material, including the ignition temperature and flux-time-product, as well as the heat release rates of the plywood at various incident heat fluxes are characterised using data measured in fifteen ISO 5660-1 cone calorimeter experiments.

The modelled fires show good agreement with early fire growth in the experiments, however, the B-RISK models tended to overestimate the upper layer temperature and depth, leading to early flashover compared to the experiments. The model is shown to be largely insensitive to the minimum temperature for flame spread and the flame spread parameter. Predicted lateral flame spread was strongly influenced by the wall surface temperature and entrainment into the upper layer which was found to be underestimated. Further work is recommended to refine the entrainment rates for burning surfaces to improve agreement between the simulated and actual fire development, and investigate the performance of the model in simulating fire growth in larger spaces with partial combustible linings.

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Some of the content of Chapter 4-5 and Chapters 7-8 were used to prepare the paper for the 14th International Conference and Exhibition on Fire Science and Engineering*: Timber Room Experiments with the Modified B-RISK Flame Spread Capability* H. Peel, C. Wade and M. Spearpoint.

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Acknowledgements

Firstly, I would like to thank my supervisor, Associate Professor Michael Spearpoint for both his technical expertise and his guidance throughout this thesis. I am also sincerely grateful for his teaching of the fire engineering course, his guidance through the thesis pathway and his encouragement of involvement with conferences.

I am very grateful to Colleen Wade of BRANZ for her support of this thesis and for her invaluable knowledge and experience, as well as her particular expertise during the week of experiments at BRANZ and modifying the B-RISK model.

I would like to thank BRANZ for funding this study, in addition, I am grateful to Haejun Park, Peter Collier, Lukas Hersche, and Peter Whiting for their assistance with setting up and running the large scale experiments, as well as their expertise with trouble shooting during the experiments.

I would also like to thank Professor Andy Buchanan for encouraging the development of this thesis topic.

Thank you to Grant Dunlop from the University of Canterbury for the time and effort spent preparing equipment for the cone calorimeter experimental work, and Bob Wilsea-Smith for his help during the experiments.

I would like to acknowledge my employer, Olsson Fire & Risk for their support over the two years of fire engineering study.

I am very grateful also to my colleagues in the fire engineering course, in particular Sahand and Ivy for fielding my questions and sharing the experience.

Thank you to Mum and Dad for their endless encouragement, and my friends for their support and patience with me over the last year, in particular Phoebe Balle for her thoughtful proof reading.

Finally, thank you to Mathew, as always, for his help and good humour over all the highs and lows of a thesis year.

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Nomenclature

Symbol	Description	Unit
A_p	Pyrolysis area	m^2
A_T	Total area under the flame spread time-distance curve	ft^2
C_n	Interpolation constant	
ε	Surface emissivity	
$k\rho c$	Thermal inertia	$kJ\ m^{-2}\ K^{-1}\ s^{-½}$
LFS_{Edge}	Lateral flame spread to the edge of the specimen	
FDP	Flaming droplets and particles produced	
$FIGRA_{RC}$	FIre GRowth RAte (Room-Corner) index	kW/s
$FIGRA$	FIre GRowth RAte (Room-Corner) index	kW/s
FO	Flashover	
FSC	Flame spread classification	
FSP	Flame spread parameter	kW^2/m^3
FSR	Flame spread rating	
FTP	Flux-Time-Product	$s(kW/m^2)^{(1/n)})$
FTP_{ign}	Flux-Time-Product at material ignition	$s(kW/m^2)^{(1/n)})$
h_c	Convective heat transfer coefficient	kW/m^2K
HRR	Heat release rate	kW
$k\rho c$	Thermal inertia	$kJ\ m^{-2}\ K^{-1}\ s^{-½}$
LFS	Lateral Flame Spread	
LFS_{Edge}	Lateral flame spread to the edge of the specimen	
n	Flux time product index	
ρ	Density	kg/m^3
$\dot{q}_e^{"}$	Sum of the incident heat flux to room surfaces	kW/m^2
$\dot{q}_{cr}^{"}$	Critical heat flux per unit area	kW/m^2
$\dot{q}_{ff}^{"}$	Flame front heat flux per unit area	kW/m^2
$\dot{Q}(t)$	Total heat release	MJ
$\dot{Q}_b(t)$	Total heat release from burner	MJ
r^2	Correlation coefficient	
$SMOGRA$	SMoke GRowth Rate index	m^2/s^2
THR_{600}	Total heat released over the first 10 min of SBI test	MJ
t	Time	s
T_b	Minimum thermocouple temperature	˚C

t_{ig}	Time at ignition	s
t_{max}	Time at peak release rate	s
T_{max}	Maximum thermocouple temperature	˚C
$T_{s,min}$	Minimum temperature for flame spread	K
TSP_{600s}	Total smoke produced over the first 10 min	m^2
T_∞	Ambient Temperature	K
v_p	Flame front velocity	m/s
X_{O2}	Volume fraction of oxygen	ppm
y	Distance from end of specimen	m
y_p	Location of upward pyrolysis front	m
y_f	Upward flame length	m
θ_c	Temperature rise of flue gases	K
θ_m	Temperature rise of flue gases during test calibration	K
φ	Flame spread parameter (ASTM E1321)	kW^2/m^3

1. Introduction

1.1 Significance of Flame Spread in Fires

It has been well documented that the choice of internal surface linings is a factor in the rate of fire growth and consequently influence the outcome of a fire. Karlsson and Quintiere (2000) observed that a fuel package with a large surface area such as a wall or ceiling lining will burn much more rapidly than the equivalent fuel package with a smaller surface area. There are recent examples of catastrophic fires where the interior surface linings have been identified as a major factor in ignition and/or fire growth. These include ‘The Station’ nightclub fire in Rhode Island in 2003 (Madryzkowski, Bryner, Grosshandler, & Stroup, 2004), and the ‘Kiss Nightclub’ fire, Brazil in 2013 (Atiyeh, 2013).

Despite the observable contribution of interior linings to fire development, flame spread on wall and ceiling linings is difficult to accurately predict. This difficulty is due to the wide range of possible lining products and performance, as well as the diversity in product layout and configuration.

1.2 Impetus for Research

Despite improved methods of testing surface lining fire performance, it is still difficult for legislators to address the enormous variation in building design when seeking to control surface linings in order to achieve required fire safety outcomes. Studhalter (2012) summarises many of the uncertainties associated with linings in compartment fires in Table 1.1.

Table 1.1: Uncertainties influencing the risk associated with linings during fire growth (Studhalter 2012)

Timeline		
↓	1.	Probability of ignition – does **ignition of an item** take place?
	2.	Does the first ignited item release enough energy and is it located closely enough to the lining, so it can **ignite the lining?** Alternatively, can it ignite other items which can then ignite the lining?
	3.	If linings are ignited – are the lining configuration and the environmental conditions in such a way that **flames can propagate on the lining?** How fast do they propagate?
	4.	Are **other items involved** in fire spread (ignited by the first ignited item or the lining) and contribute to the fire growth in the room? How many of them are present, and what is their spatial arrangement? What are their ignition and burning characteristics?
	5.	Are **occupants present** in the room of interest? What is their state of alertness and ability to escape?
	6.	Are **detection or suppression systems** present which can influence events 2. to 5.?

The ability of building owners and compliance authorities to control each uncertainty varies, for example, it is difficult to consistently control and predict the presence of other items and their spatial arrangement whereas the presence of active systems can be controlled through legislation. Similarly, the propensity of flame spread of material can be somewhat controlled by testing and comparing different lining materials.

However, to control the overall contribution of surface linings to fire development in buildings, many jurisdictions currently use prescriptive surface lining control systems. These systems usually refer to a number of tests and standards to assess the fire hazard associated with each lining (these are described in detail in Chapter 2). These control systems restrict both the lining type (by fire hazard or material type) and its application (for example, the compartment size and occupancy). Even in otherwise performance-based design regulations, requirements for surface finishes in design legislation would generally assume (as a worst case) that the room or area could be fully lined with materials no better than the minimum required classification. Any exception to these rules, such as allowing for items such as door jambs and light fittings, permit very small areas only. The assumption that all surfaces in a space have similar fire performance can be conservative, particularly given the enormous range of lining materials available to designers. The Building Code of New Zealand, for example, was changed in 2012 to include more rigorous restrictions for combustible linings in some spaces (see Section 2.8).

The assumption that a room will be fully lined with the worst acceptable lining type is particularly restrictive when only small amounts of non-compliant linings are desired, or rooms are intended to have combinations of linings, even when the rooms themselves have a large total surface area. The study therefore investigates the effect of combining partial combustible (timber) linings, which are perceived to provide rapid fire spread in a compartment with non-combustible linings. To aid the development of more refined design methods for internal linings, the contribution of various configurations of partial combustible linings to fire development will be compared experimentally, and the feasibility of modelling of flame spread on partial linings using a modified version of B-RISK will be assessed.

1.3 Research Objectives

This work seeks to contribute to understanding the importance of the extent of interior linings to fire development and provide data and tools for further investigation.

The objectives are:

1. To understand how interior linings, particularly untreated timber linings, contribute to fire development and how this currently is addressed by building codes in different jurisdictions.
2. To investigate how reducing the extent of timber linings in a space can affect the severity of a fire.

3. To examine the feasibility of modifying the existing flame spread model in the B-RISK zone model to enable simulations of fires in partially lined enclosures.

The research has four tasks:

1. Investigate and compare the fire design legislation surrounding internal wall and ceiling linings of commercial buildings in the U.S.A., Canada, UK, Europe, Australia, and New Zealand and to describe the relevant fire tests which these lining materials must undergo according to the requirements for each jurisdiction. Identify the similarities between codes internationally and the scientific and cultural reasoning for common interior lining regulations for fire.
2. Experimentally compare the contributions of various configurations of partial timber linings to fire development in the standard ISO 9705 room, in particular heat release rate and time to flashover, as well as layer temperature and depth. Seven modified ISO 9705 tests are undertaken where the same timber product is installed in different configurations.
3. Evaluate the capability of a modified version of the B-RISK zone model to predict time to flashover in the ISO 9705 room when partially lined with timber, as well as its sensitivity to various parameters. To this, fifteen small scale cone calorimeter tests are first carried out on timber lining samples to characterise the lining material for input into the modified B-RISK model. The results of the ISO 9705 tests with partial timber linings are compared with predictions of the time to flashover and upper layer height and temperature made by B-RISK.
4. Recommend further work to improve the capacity to predict surface lining performance in enclosures where there are multiple linings in a single space.

Since the New Zealand Building Code with regards to interior linings was changed in 2012 (for details, see Section 2.8), there is a perception that timber linings in particular are now treated more conservatively when designing for fire (Buchanan & Parker, 2014). This study investigates this perception by assessing whether the New Zealand requirements for timber linings in particular are on par with international prescriptions. It also seeks to evaluate whether more timber can safely be used than presently allowed in certain spaces by using thin timber plywood as the lining type when experimentally investigating the effect of partial combustible linings on fire growth.

From a research perspective, it is useful to use timber linings when conducting experiments into the performance of partial combustible linings, as there already exists a body of work into the fire performance of timber which is valuable for comparison with the findings in this thesis (See Section 3.2). Furthermore, timber is relatively combustible compared to other common lining products such as plasterboard or even vinyl wallpaper (Collier, Whiting, & Wade, 2006), which means findings relating to its fire performance could (cautiously) be used as a benchmark for comparison with other, less combustible products. Timber is also readily available and economical, with low toxicity and minimal additional preparation of samples required.

1.4 Thesis Structure

The layout of this thesis is as follows:

Chapter 2 Review of Code Requirements for Timber Linings summarises the requirements for internal linings, in particular wooden linings and compares how they are addressed in design guidance in Australia, New Zealand, the U.S., the U.K, and Canada. In this chapter, the fire tests required by each jurisdiction are described, and then the design guidance which calls these tests are summarised and compared.

Chapter 3 Background to Flame Spread Modelling outlines existing flame spread theory, the established principles of the compartment fire and the roles that flame spread plays therein, as well as existing research into timber linings in compartment fires. This research is applied to zone models and the existing research into zone models for modelling flame spread is outlined.

Chapter 4 Modified B-RISK Flame Spread Capability describes the modified B-RISK model for fire development of compartments partially lined with combustibles. It details the modifications made to the existing model to enable the performance of partial linings to be predicted. It also outlines some model inputs as derived from the literature.

Chapter 5 Cone Calorimeter Testing describes the small scale testing undertaken using the cone calorimeter to measure the required properties of the timber linings so that these could be modelled using B-RISK. This chapter includes the small scale test results.

Chapter 6 Partially Lined ISO 9705 Experiments describes the methodology and approach of seven large scale experiments undertaken to ISO 9705 except the walls and ceilings are partially lined with timber. The results are reported on and briefly discussed. A ranking system to facilitate comparison is proposed.

Chapter 7 B-RISK Modelling of Partially Lined ISO 9705 Experiments reports on the modelling method and describes the inputs which were derived from the cone calorimeter tests and the literature. This chapter describes the results of the modified B-RISK model of the ISO 9705 tests, and compares these with the experimental results. A sensitivity analysis is included to ascertain the relative effect of varying inputs into the B-RISK model on the accuracy of the model predictions.

Chapter 8 Summary This chapter summarises the limitations of the experimental work and its underlying assumptions. This chapter reviews the work undertaken, and includes a Conclusions section where the key findings are summarised and recommendations are made to where further research is required.

The work described in this thesis has also been reported in two conference papers presented in 2016. The full scale experimental work was described in the paper, *Experiments to develop a performance based assessment method for rooms partially lined with timber* written by the author of this thesis, Colleen Wade, Dr Michael Spearpoint and Charles Fleischmann, and was presented by Charles Fleischmann at the 11th Conference on Performance-based Codes and Fire Safety Design Methods in 2016.

The preliminary modelling method and results were reported in the paper, *Comparison of Partially Lined Timber Room Experiments with the Modified B-RISK Flame Spread Capability* by this author, Colleen Wade and Michael Spearpoint and presented by the author of this thesis at Interflam 2016.

2. Review of Code Requirements for Timber Linings

2.1 Overview

This purpose of this chapter is to report on fire design legislation surrounding the use of timber interior wall and ceiling linings of commercial buildings in the U.S.A., Canada, U.K., Europe, Australia, and New Zealand and to describe the relevant fire tests which lining materials must undergo according to the requirements for each jurisdiction. This first part of this section (Section 2.2) includes descriptions of the legislated tests used to classify and compare internal linings. Sections 2.3 to Section 2.8 outline the controls for interior linings for fire in each jurisdiction and their particular classification methods using the described tests. This review focuses on the prescriptive requirements for each jurisdiction, as the propensity of the various building requirements to enable performance based design for wall linings varies between regions and did not provide meaningful comparison.

The fire tests can be qualitatively separated into large scale, intermediate scale and bench scale tests. Large scale tests include an enclosure which could reasonably mimic a life sized building compartment. Intermediate scale test use equipment which are not intended to accurately replicate the size or shape of realistic building compartments but generally necessitate some form of enclosure, lined with several square metres of candidate material. Bench scale tests are carried out using specialised equipment but do not require the construction of an enclosure, and use less than 1 m^2 of candidate lining material.

In some jurisdictions, testing for fire performance can be undertaken to either full scale or to small scale. The small scale test is often favoured by commercial lining product providers as it is cheaper to perform. However, it is usually noted in these jurisdictions, for products that cannot accurately be replicated at small scale testing to full scale is mandatory. Examples of products which cannot be accurately represented in small scale tests are those that fall away, drip away, have irregular surfaces or require fixing or jointing details which affect its fire performance.

Many of the tests and standards referred to in this section are amended regularly. It is noted which amendment for each test has been referred to in each section, however, as standards are re-worked, variations are expected between versions of the same standard and between standards largely accepted as equivalent.

2.2 Internal lining Tests

2.2.1 Large Scale Tests

2.2.1.1 EN 14390:2007- Large-scale room reference test for surface products

The EN 14390: 2007 large scale test measures the burning behaviour of building products (specifically interior linings) in a room scenario. It is also referred to as the ISO 9705:1993, BS 476-33:1993, and AS ISO 9705:2003 – these are identical tests (Sundström, 2007). The enclosure used in the EN 14390:2007 test is shown in Figure 2.1. The principal output is the time to flashover which is defined as when the total heat release rate reaches or first exceeds 1 MW. The smoke production rate is also measured and recorded during the test. This test is the reference scenario for a number of small scale tests including the Single Burning Test (See Section 2.2.2.1).

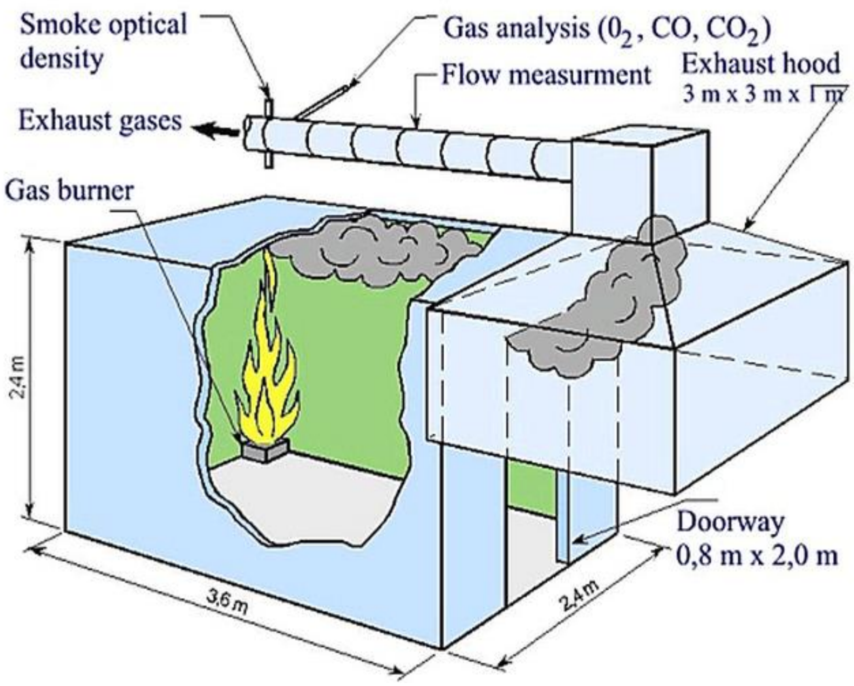

Figure 2.1: ISO9705:1993 Enclosure and Fume Hood - SP Swedish National Testing and Research Institute

The internal room measurements are 3.6 m length by 2.4 m width by 2.4 m in height, with a doorway in one of the shorter walls measuring 0.8 m by 2.0 m in height. The walls and ceiling, except for the wall with the door opening, are fully lined with the candidate lining product. A square propane gas burner measuring 0.17 m by 0.17 m by 0.145 m high is located in one of the corners away from the doorway and produces a heat release rate of 100 kW for the first 10 min of the test, and then 300 kW for the following 10 min, giving a total test time of 20 min The combustion gases are collected through a hood outside the door, and are used to measure the heat release rate and smoke production. Flashover is deemed to have occurred when the heat release rate reaches 1 MW. Flame spread along walls and ceiling can be observed visually.

2.2.1.2 ASTM E 2257-13a Standard Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies

ASTM E2257-13a is referred to as "*the American version of ISO 9705.*" (Horrocks & Price, 2008). It is very similar to the EN 14390:2007, with some differences arising from differences in units of measurements between U.S.A and the international system. ASTM E2257-13a requires a room measuring 2420 mm by 3630 mm by 2420 mm high (8 ft by 12 ft by 8 ft high) with a doorway in the centre of one of the 2420 mm by 2420 mm walls measuring 780 mm by 2015mm in height. Note 3 of the ASTM E 2257-13a states that the compartment dimensions and tolerances have been chosen to make it convenient to utilise the standard U.S. size 1.22 m by 2.44 m (4 ft by 8 ft) building materials or panels as well as the standard 1.2 by 2.4 m panel sizes common outside the U.S.A, therefore theoretically enabling the same room used in an EN 14390/ EN ISO 9705 test to also be used for an ASTM E2257-13a test. The ASTM E2257-13a burner is also a 0.17 m by 0.17 m square propane diffusion burner located in the corner of the room with the surface of the burner located 0.3 m above the floor, flush with the walls. The heat output from the burner must be 100 kW for the first 10 min, followed by 300 kW for the following 10 min (Anon., 2003).

2.2.1.3 2015 NFPA 286 Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth

NFPA 286 is a large scale fire test, which can be used to measure flame spread on lining materials. This test uses a similar test set up to the EN 14390 test, however, there are modifications to the room dimensions, heat release rate and performance criteria.

The interior dimensions of the floor of the fire compartment used in the NFPA 286 test, when the specimens are in place, measures 2.44 m (8 ft) ± (2 in) by 3.66 m (12 ft) ± 0.051 m (2 in). The finished ceiling is 2.44 m (8 ft) ± 0.051 m (2 in) above the floor. The four walls are at right angles defining the compartment. The compartment contains a 0.78 m (30.75 in) ± 0.02 m (0.75 in) by 2.02 m (79.5 in) ± 0.02 m (0.75 in) doorway in the corner of one of the shorter (2.44 m by 2.44 m) walls. A 0.305 m by 0.305 m (12 in by 12 in) gas burner is located 0.305 m above the floor in the left corner away from the door to provide 40 kW of heat exposure for the first 5 min, which is then increased to 160 kW for a further 10 min (Anon., 1998).

Annex C of the NFPA 286 standard outlines the conditions which an interior finish material must meet to be considered satisfactory:

(1) During the 40 kW exposure, flames should not spread to the ceiling.

(2) During the 160 kW exposure, the interior finish should comply with the following:

  (a) Flame should not spread to the outer extremity of the sample on any wall or ceiling.

  (b) Flashover should not occur.

(3) The peak rate of heat release throughout the test should not exceed 800 kW.

(4) The total smoke released throughout the test should not exceed 1000 m^2.

2.2.2 Intermediate Scale Tests

2.2.2.1 EN 13823:2002 Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item

The EN 13823:2002 reaction to fire test (abbreviated to Single Burning Item or SBI test) was developed to simulate the burning of a single item, such as a wastebasket in the corner of a small room and is used to class products according to the Euroclass ranking system (Anon., 2002). It was designed to produce results which can be matched with to the ranking (referred to as Euroclass, see Section) that would be obtained for the same product tested in the ISO 9705:1993/EN 14390:2007 test.

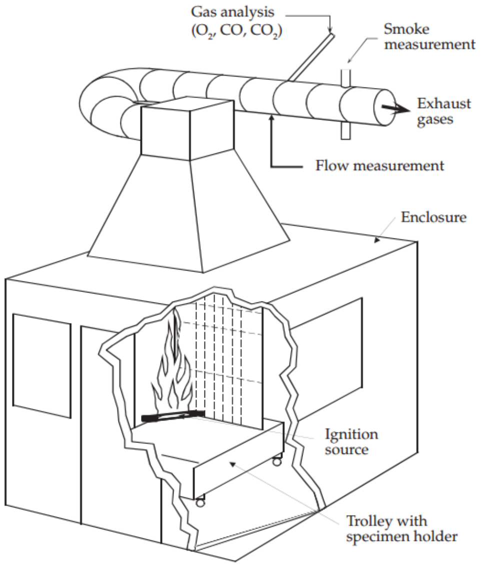

Figure 2.2: Single Burning Item Test Sample and Enclosure (van Mierlo & Sette, 2005)

The test apparatus is shown in Figure 2.2. The test requires two 1.5 m high samples of the candidate lining, measuring 1 m and 0.5 m wide respectively, which are configured to represent a room corner. The apparatus is located within a test room measuring 3 m in length by 3 m in width by 2.4 m in height. A triangular shaped propane diffusion gas burner running at 30 kW is the heat and ignition source for this test, and it is located at the base of the corner. The test runs for 20 min, during which time combustion gases are collected in a hood. The SBI test is used to classify linings according to the Euroclass scheme using the following outputs:

- Speed of growth of heat release rate (converted to index known as FIGRA- FIre GRowth RAte, W/s)
- Total heat released over the first 10 min (THR_{600s} – Total Heat Release in MJ)
- Rate of flame spread to the edge of the specimen (LFS_{Edge}, observed as whether flame spread reaches the edge of the specimen)
- Rate of smoke production and (converted to an index – SMOGRA – SMoke GRowth RAte in m^2/s^2)
- Total smoke produced over the first 10 min (converted to TSP_{600s} in m^2)
- Flaming droplets and particles produced (a parameter referred to as FDP, observed as whether or not flaming droplets form, and whether or not they remaining flaming for 10 s or less)

2.2.2.2 ASTM E-84-15b Steiner Tunnel Test - Standard Test Method for Surface Burning Characteristics of Building Materials

ASTM E-84 - Standard Test Method for Surface Burning Characteristics of Building Materials (ASTM E-84) (Anon., 2015) is the test used to evaluate the flame spread characteristics of surface linings in the U.S.A. This test requires that the lining material that is being tested is located in the "ceiling" position of an enclosed tunnel furnace measuring 0.46 m (18 in) wide by 0.305 m (12 in) deep by 7.62 m (25 ft) long. The test sample is required to be 0.46 m (18 in) wide by 7.3 m (24 ft) long. The tunnel is equipped with two gas burners at one end which direct a flame of 88 kW onto the surface of the test material. Air enters the tunnel by means of an induced-draft system via a slit upstream of the burner. Double –glazed observation windows are located on one side of the apparatus so that the flame spread along the surface of the material can be observed during the test. The distance along which the flame travels as well as the rate at which the flame front advances until the specimen is entirely consumed or a maximum of 10 min of exposure determines the calculated flame spread index. To provide standard conditions for each test, the tunnel is calibrated to an index of 0 for non-combustible materials (usually cement board) and 100 for flame spread rate along a sample of Red Oak flooring. However, indices for the materials tested to ASTM E-84 can range from 0 to over 1000.

To obtain the Flame Spread Classification (*FSC*) of the material, the distance travelled by the flame frontis plotted as a function of time. If the total result area A_T under the flame spread time versus distance curve $\leq$ 97.5 ft min (1783 m s^{-1}) then,

$$FSC = 0.515 \times A_T \qquad [2.1]$$

If A_T > 97.5 ft min (1783 m s $^{-1}$) then,

$$FSC = \frac{4900}{195 - A_T} \qquad [2.2]$$

ASTM-E84 has been identified as being unreliable for lining materials which drip or fall away as this test relies on the lateral progression of flame through the tunnel. This means that linings which drip, or fall away as a result of the heat or flames will not show flame progression in the test but may still contribute to fire development in a real fire scenario.

2.2.2.3 CAN/ULC S102.2-07 Test for Surface Burning Characteristics of Flooring, Floor Coverings and Miscellaneous Materials and Assemblies

CAN/ULC S102-03 refers to the Canadian test for wall, ceiling and floor lining performance (Anon., 2007). CAN/ULC S102-03 uses a similar Steiner Tunnel apparatus as in the ASTM E-84 test, however the observation windows in the Canadian test are single glazed. This creates turbulence in the Tunnel, while in the U.S. ASTM E84-15b test, turbulence is created by placing bricks on the tunnel floor. Products which are tested and classified according to the ASTM E-84 test cannot be assumed to achieve the same classification to the CAN/ULC test.

CAN/ULC S102-03 also requires different evaluation of the experimental results to find the Flame Spread Rating (*FSR*) compared to the ASTM E-84 test. The CAN/ULC S102-03 evaluation method is intended to take account of products (such as foams and plastics) whereupon the flame front may advance quickly during the early stages of the test and subsequently slow or even fail to reach the end of the specimen. Three different types of *FSR* value, FSR_1, FSR_2, and FSR_3 can derived for a product depending on whether the flame front continues to advance rapidly throughout the test or eventually slows down. The *FSR* for most materials, FSR_1 the distance travelled by the flame front is plotted graphically as a function of time, if the total area A_T under the flame spread time-distance curve is $\leq$ 29.7 m min (0.495 m s^{-1}) then,

$$FSR_1 = 1.85 \times A_T \qquad [2.3]$$

Otherwise, if A_T > 29.7 m min (0.495 m s^{-1}) then,

$$FSR_1 = \frac{1640}{59.4 - A_T} \qquad [2.4]$$

$FSR_{2'}$ and FSR_3 can be found using alternative tests and correlations for materials where the flame front may advance rapidly during the initial stages of the test and subsequently slow or even fail to reach the end of the specimen. This is not a reported phenomenon for wood products, so is not discussed here.

2.2.3 Bench Scale Tests

2.2.3.1 ISO 5660-1:2002 Heat release rate (cone calorimeter method)

This test uses the cone calorimeter, which is bench scale device that includes a conical radiant heater to expose a sample of lining material to range of heat fluxes and can measure ignition time, mass loss, combustion products and heat release rate (Anon., 2002). A sketch of the cone calorimeter is shown in Figure 2.3. The ISO 5660-1:2002 is accepted in some jurisdictions as indicator of performance of products to the full scale ISO 9705:1993, however it is not permitted to used to demonstrate performance to EN 14390).

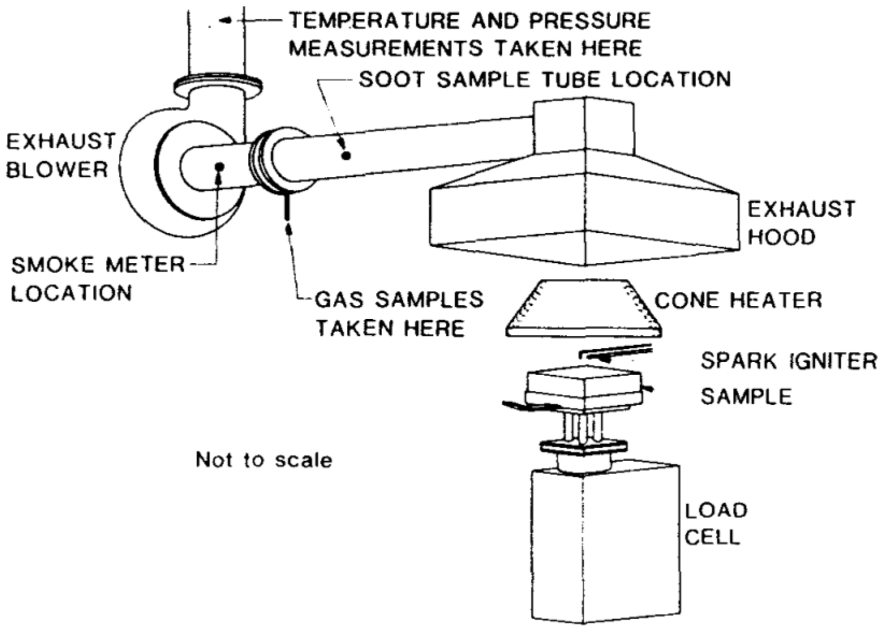

Figure 2.3: Cone calorimeter test apparatus (Babrauskas & Parker, 1987)

The ISO 5660-1:2002 test involves exposing a 0.1 m by 0.1 m sample of the candidate lining material to a specific irradiance in a horizontal configuration. The latest cone calorimeters are capable of providing exposure conditions ranging from 10 kW/m^2 to 100 kW/m^2. However, the irradiance for product testing is not stipulated in the test standard itself, but is defined by the building code or legislation which calls for the test, for example, in New Zealand, the required irradiance for product testing is 50 kW/m^2 (New Zealand Government, 2014), whereas some U.S.A. military standards required testing at 100 kW/m^2 irradiance (Babrauskas, 1993).

Ignition is piloted using a spark plug located 13 mm above the centre of the upper face of the specimen. The test ends under the following circumstances:

- 30 min have elapsed and no sign of ignition has been observed
- X_{O2} (the proportion of oxygen in combustion gases) returns to the pre-test value within 100 parts per million of oxygen concentration for 10 min
- The mass of the specimen becomes zero.

The ISO 5660-1:1993 test and the BS 476-15:1993 are identical tests. Both these tests were replaced by the ISO 5660-1:2002. During the writing of this report, ISO 5660-1:2015 was released to replace ISO 5660-1:2002 (referred to in the U.K. as BS ISO 5660-1:2015).

2.2.3.2 AS 3837:1998 Heat release rate (cone calorimeter method)

The Australian AS 3837:1998 (Anon., 1998) test is largely similar to the ISO 5660-1:2002 test. The most critical difference is the end of test criteria, which are as follows:

The test ends when:

- no ignition after 10 min
- no signs of combustion
- mass loss rate < 150 g/m^2 averaged over one minute
- 60 min from test start

These criteria can mean that for materials where it fails to ignite properly and/or the mass loss rate drops below 150 g/m^2 (averaged over one minute) the classification results to AS3837:1998 can differ from those achieved using the ISO 5660-1:2002.

2.2.3.3 BS 476-7:1997 Method for Classification of the Surface Spread of Flame of Products

Part 7 of BS 476 (Anon., 1997) specifies a bench scale test method to test the spread of flame along the surface of a product.

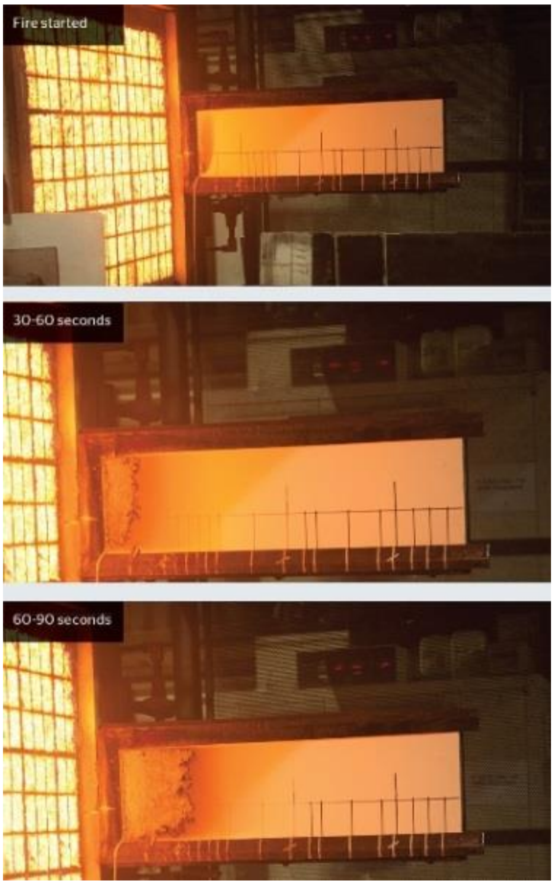

Figure 2.4: BS 476-7 Test– image retrieved from building.co.uk

The test is 10 min in duration and involves exposing a rectangular sample measuring 885 mm in length by 270 mm in width to heat from a radiant panel located perpendicular to the face of the specimen, as shown in Figure 5. The radiant panel must be calibrated to achieve an irradiance of 32.5 kW/m^2 on the face of the specimen at a distance of 75 mm from the panel surface, and must achieve a range of reduced irradiance values at intervals further away from the panel. The rate of flame spread is evaluated at 1.5 min and at 10 min to provide a Class Rating ranging from 1 (slowest flame spread) to Class 4 (most rapid flame spread).

2.2.3.4 BS 476-6:1989 – Method of Test for Fire Propagation for Products

Part 6 of BS 476 (Anon., 1989) is used to establish a fire propagation index to identify the temperature increase required by a product to propagate a flame and quantify the flame propagation of a lining material (Anon., 1989). It is considered to be more severe than BS 476-7 and is generally used to investigate materials which have been demonstrated to achieve a Class 1 rating according to BS 476-

7:1997 to show that these conform to the more stringent Class 0 rating. To achieve a Class 0 rating, a material must be wholly non-combustible or must meet the requirements of Class 1 when tested to BS 476-7, as well as demonstrate a sub-index $i_1 \leq 6$ and a total index $I \leq 12$ when tested to BS 476-6.

The BS 476-6 test involves exposing a 225 mm x 225 mm by maximum 50 mm thick sample, oriented vertically to the 14 jets of gas pipe burner with a heat release rate of 530 W at a distance of 3 mm (Figure 2.5). After 2 min 45 s, two electric elements with a heat release rate of 1800 W are switched on. The output of these elements s then reduced to 1500 W after 5 min and maintained constant until the end of the test (20 min).

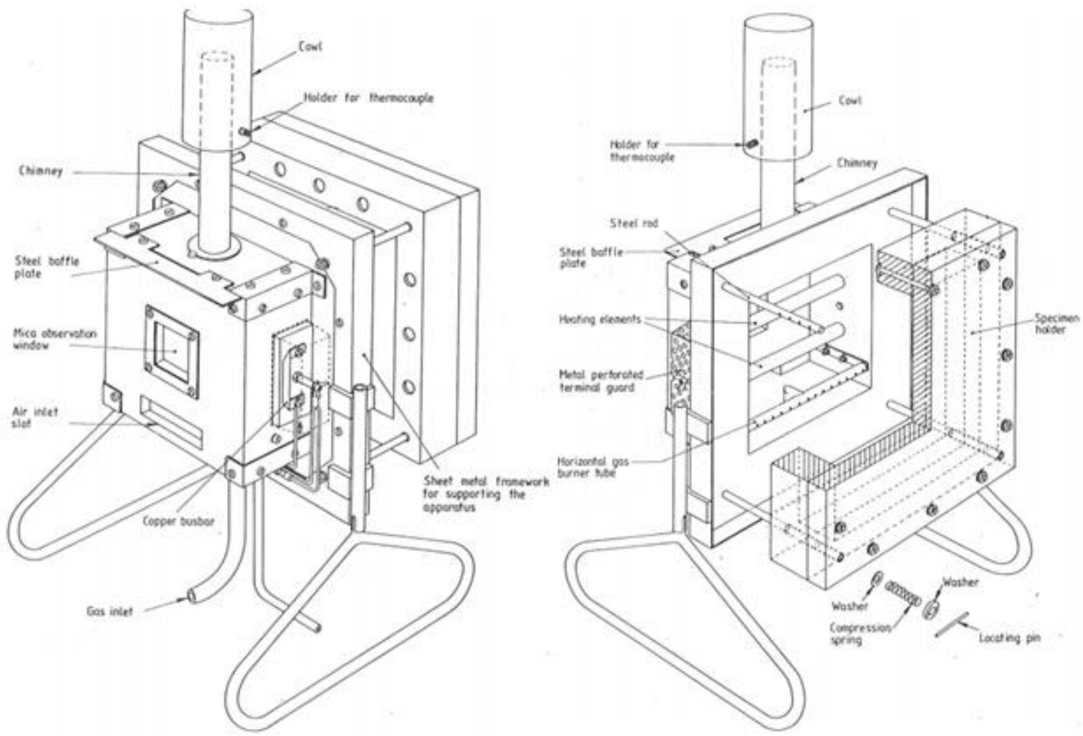

Figure 2.5: BS 476:6 Apparatus (Anon., 1989)

The difference between the ambient temperature and that in the chimney is recorded continuously using thermocouples, and compared to a calibration curved derived from the same test of asbestos-cement board. The sample is evaluated by comparing the calibration curve and test curve at 30 s intervals from the test start until 3 min to find i_1, then at 1 minute intervals from 4 min to 10 min to find i_2, and then at 2 minute intervals from 12-20 min to find i_2. The indices are calculated as follows:

$$i_1 = \sum_{1/2}^{3} \frac{\theta_m - \theta_c}{10t} \ , \ i_2 = \sum_{4}^{10} \frac{\theta_m - \theta_c}{10t} \ \ , i_3 = \sum_{12}^{20} \frac{\theta_m - \theta_{c,}}{10t} \qquad [2.5]$$

where $\theta_c = temperature\ rise\ of\ the\ flue\ gases\ (K)\ during\ test\ calibration$
and $\theta_m = temperature\ rise\ of\ the\ flue\ gases\ (K)\ during\ test$

2.2.3.5 EN ISO 11925-2:2010 - Single Flame Ignitability (SFI) test

The EN ISO 11925-2 test (Anon., 2010) simulates a cigarette lighter size flame being placed upon either the surface or the edge of the 0.25 m by 0.09 m specimens for a short duration (15 s or 30 s). The time to ignition, the extent of flame spread, $F_{S,}$ and the time until the flames spread up and exceed 150 mm above the flame application point are recorded. The maximum test duration is 60 s, however if no signs of ignition are present it may be terminated earlier.

Wood products generally withstand exposure for 30 s, without flame spread reaching 150 mm.

2.2.3.6 ASTM E1321 – 97a – Lateral Ignition Flame Transport (LIFT) test

ASTM E 1321 (Anon., 2013) is also known as the lateral ignition flame transport (LIFT) test and is used for determining material ignition and flame spread properties. It is not currently used for product regulations, however it is an important test as several well-known flame spread models, including that of Quintiere (Quintiere J. , 1993), use inputs derived from this test. The apparatus used is described in ASTM E 1317. ASTM E 1321-97a describes a two-part test and the theory used to interpret the results. The first test is an ignition test to identify the critical surface heat flux for ignition, the minimum ignition temperature and the thermal inertia value, $k\rho c$. The second test is a flame spread test, from which the minimum lateral spread flux, the minimum lateral spread temperature, $T_{s,min,}$ and the flame heating parameter, φ (which relates the flame spread rate on a material to the incident heat flux and material properties derived from the ignition test) can be derived.

The following description is of the flame spread test and measurements of ASTM E 1321-97a. Details of the ignition test can be found in the Standard.

During the ASTM E 1321 flame spread test, a 155 mm wide x 800 mm long test sample is located in a frame exposed to a heat flux distribution generated by a radiant panel which measures 280 mm wide by 483 mm long. The sample is angled at 15° ± 0.25° to the face of the burner. The hot end of the sample is 125mm away from the face of the burner, and offset from the edge of the burner by approximately 125 mm (Figure 2.6). The heat flux is graduated so that the specimen is exposed to a heat flux that is approximately 5-10 kW/m² higher at the hot end (50 mm from the edge of the sample) than the minimum heat flux necessary for ignition (Figure 2.7). This means that a single experiment can provide flame spread rates over a variety of incident heat fluxes. At the start of the flame spread test, once the heat of the burner has stabilised, the sample is positioned in the frame and preheated until thermal equilibrium is reached (the sample is the same temperature throughout its thickness), then the sample is ignited at the end of sample closest to the panel by a non-impinging acetylene-air flame.

To measure flame front velocity, a horizontal line is drawn along in the middle of the sample throughout its length and vertical marks are drawn at 25 mm intervals. The progress of the flame front is timed along the sample, using the reference points marked on the sample.

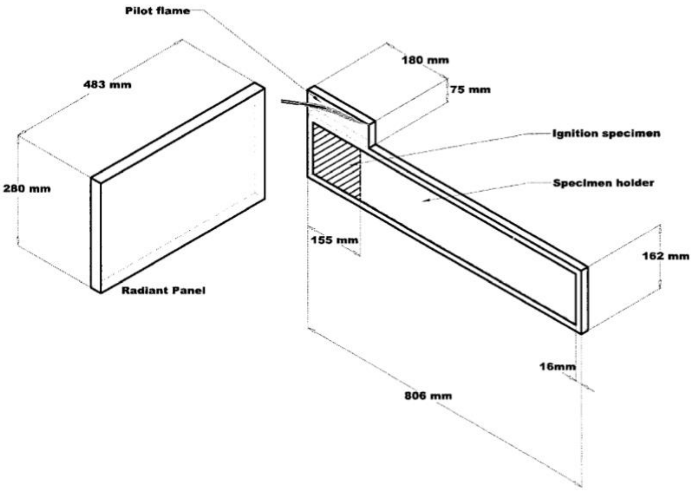

Figure 2.6: Layout of radiant panel and test specimen for ASTM E 1321 test –angle between panels is exaggerated to show panel features (Leung, C.W. & Chow, 2001)

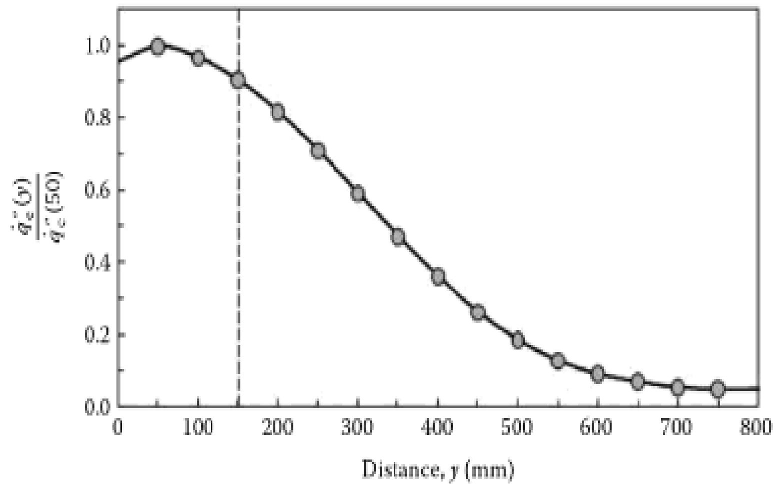

Figure 2.7: Required heat flux for LIFT test as a function of distance along the sample, $\dot{q}_e''(y)$ as a ratio to the heat flux 50 mm from the closest edge of the sample to the burner, $\dot{q}_e''(50)$ (Huynh, 2003)

The method of finding the minimum lateral spread temperature $T_{s,min,}$ and the flame spread parameter, φ is described within the ASTM E 1321 standard. The method is based on the work by Quintiere, Harkleroad et al. (1985).

In summary, the minimum temperature for flame spread, $T_{s,min,}$ is found by extrapolating the flux – temperature profile at each corresponding heat flux, and identifying the heat flux at the maximum distance reached by the flame front from the hot end of the sample, and converting this to a temperature.

The flame spread parameter can be derived from the following (Wilkie & Morgan, 2010),

$$\varphi = \frac{\frac{4}{\pi}}{(Cb)^2}$$

where *b* is a material property calculated from the ignition test and heat loss at the time of ignition, *C* is the slope of the linear fit of $\frac{1}{\sqrt{V_p(y)}}$ where v_p is the flame front velocity at *y* distance from the end of the specimen closest to the burner, plotted as a function of $\dot{q}_e^{"}(y)$ or the heat flux as a function of distance along the sample.

2.3 Wall and Ceiling Regulations by Jurisdiction – U.S.A

2.3.1 Code Situation

The relevant building codes and regulations in the U.S.A vary by region and jurisdiction. Local municipalities are permitted to adopt their own building code version and there is no nationally mandated building code or set of regulations relating to fire protection and design. Until the start of the twenty-first century, three model building codes were used in various regions (van Hees & Blomqvist, 2007). These were:

- BOCA National Building Code (BOCA/NBC) by the Building Officials Code Administrators International (BOCA) which predominated in the Midwest and Northeast
- Uniform Building Code (UBC) by the International Conference of Building Officials (ICBO) which was used in the western USA.
- Standard Building Code (SBC) by the Southern Building Code Congress International (SBCCI) which was referred to in the South.

However, the differences in the code requirements above presented difficulties for material suppliers and designers. The further development of these codes ceased in 2000, and was replaced with the International Building Code (IBC) (International Code Council, Inc., 2009). This code can be used in conjunction with the International Fire Code, which regulates the management and occupation of a building, with regards to fire safety.

The alternative to the International Building Code when designing buildings for fire safety is the NFPA Life Safety Code, or NFPA 101 (National Fire Protection Association, 2015). The NFPA 101 is a standard, not a legal code but it is designed and intended to be adopted into law where mandated.

2.3.2 Classification of Lining Materials

2.3.2.1 International Building Code

The International Building Code classifies wall and surface linings into three categories, or "Classes," A, B or C based on their flame spread performance. The fire test used to evaluate the flame spread characteristics of the surface linings is the ASTM E-84, Standard Test Method for Surface Burning Characteristics of Building Materials as described in Section 2.2.2.2. The ratings obtained from the ASTM E-84 test are grouped into the following classifications:

> Class A is the lowest rates of flame propagation, with a flame spread rating range of 0-25, when tested to ASTM E-84

Class B refers to a flame spread rating range of 26-75, when tested to ASTM E-84

Class C refers to a flame spread rating range of 76 – 200, when tested to ASTM E-84.

As an alternative to ASTM E-84, materials can be tested to the full scale test NFPA 286 – materials which meet the criteria of NFPA 286 (described in Section 2.2.1.3 of this thesis), may be used where a Class A classification is required.

2.3.3 NFPA Life Safety Code

The NFPA Life Safety Code uses the same criteria as the International Building Code for specifying the Class rating based on the ASTM E-84 test and/or the NFPA 286 test.

2.3.4 Timber Classification

The US Wood Council reports that most timber achieves a flame spread rating of less than 200, or Class C classification when tested to ASTM E-84; however, there is no generalised class for timber. Table 2.1 shows that some timber species can achieve Class B in the ASTM E-84 test without additional fire retardant coating. (American Wood Council, 2010).

Table 2.1: Test results to ASTM for Class B Timber Products (American Wood Council, 2010)

Timber (19 mm thickness)	**ASTM-E84 rating**
Douglas Fir	70-100
Western Red Cedar	70
Spruce	74
Western White Pine	75
Western Larch	45

2.3.5 Permitted Locations of Timber Linings

2.3.5.1 International Building Code

The International Building Code (International Building Code, 2009) divides occupancies, for the purposes of surface linings, into fourteen occupancies or groups of occupancies. The spaces in each building are divided into the following three categories:

- Interior exit stairways, interior exit ramps and exit passageways
- Corridors and enclosure for exit access stairways and exit access ramps
- Rooms and enclosed spaces

Sprinklered buildings generally have a reduced requirement for surface linings. In general, a sprinklered building would be permitted a class of wall linings that is one class above that of the same space in an equivalent non-sprinklered building (e.g. where Class C is permitted in a non-sprinklered building space, that same space, if sprinklered, would be permitted Class B linings.

In general, of the three categories of space in the building, interior exit stairs, ramps and passage ways have the most stringent requirements for surface linings. Most non-sprinklered public occupancies require Class A in exitways, interior exit ramps, exit passageways, which effectively prohibits untreated timber as linings in these spaces. The notable exception to this is permanent or semi-permanent accommodation where, for large (generally more than 16 persons) occupancies, Class B or better is permitted, while for smaller groups Class C or better is also acceptable. Assembly areas, areas providing custodial care, or transient accommodation, as well as high hazard areas, also require Class A surface linings in this area.

For corridors and enclosures for exit access stairways and exit access ramps, the requirements are less stringent than for interior stairs etc. Assembly areas, areas providing custodial care, or transient accommodation, as well as high hazard areas, require Class A surface linings, whereas the remaining spaces are permitted Class B or Class C, and therefore untreated timber linings can be used in these areas. The requirements are the least stringent for rooms or enclosed spaces, with no spaces requiring a Class A.

1.1.1a NFPA Life Safety Code

The NFPA Life Safety Code (National Fire Protection Association, 2015) classifies occupancies in a manner that is largely similar to the International Building Code – spaces are grouped into thirteen different occupant groups based on the activities of the occupants', as well as their degree of physical capacity and their relationship to one another (e.g. family groups are located in *Dwellings* compared to strangers sharing a *Dormitory*). Table 2.2 summarises the worst-case surface finish class permitted in each area for each occupancy, adapted from Annex A of the Life Safety Code. A complete table including occupancy descriptions and the terminology used for each occupancy is included in Appendix A.

In nearly all public occupancies, spaces that act as exits or directly connected to exits have the most stringent surface finish requirements (usually Class A in unsprinklered facilities, which excludes the use of untreated timber). When using the NFPA Life Safety Code, an exit refers to not only opening leading from the building, but includes "that portion of a means of egress which is separated from all other spaces of the building…to provide a protected way of travel to the exit discharge" (NFPA Life Safety Code Paragraph 3.3.83), while an exit access corridor is "that portion of a means of egress connected to an exit" (NFPA Life Safety Code Paragraph 3.3.84). Care facilities, including child minding, education and detention facilities are generally restricted to A or B rated surface finishes throughout the building. In education facilities, partitions lower than 60 in (1.52 m) Class B surface finishes are permitted where Class A would normally be required, which would enable some types of untreated timber panels in these spaces. Similarly, in healthcare facilities where patients are treated as inpatients, most areas with occupancy of more than 4 persons are obligated to have surface finishes with meet the Class A rating, however an exception is permitted in corridors where the wall surface finish up to 48 in (1.22 m) above the may be Class B. Furthermore, Class A or B stores in mercantile facilities are the only spaces where wall and ceiling surface finishes are treated separately. Class A or B facilties are, in summary, multi storey and/or large floor area mercantile spaces, are permiited a less stringent (Class C) surface finish on the walls, where the same space requires Class B or better surface finishes on the ceiling. This is also compared to Class C mercantile facilties which are single storey facilities up with floor area of up to 3000 ft^2 (280 m^2) and which are permitted Class C surface finishes throughout.

The effect of sprinklers on the permitted class rating is outlined in Section 10.2 of the Life Safety Code. Paragraph 10.8.2.1 of the Life Safety Code permits, in general, that where an approved automatic sprinkler system is installed (except in Detention facilities), Class C wall and ceiling finishes are permitted in any location where Class B is required and Class B wall and ceiling finishes are permitted in any location where Class A is required.

Table 2.2: NFPA 101 Life Safety Code Interior Finish Requirements by Occupancy (adapted from Annex A of the 2015 Life Safety Code)

Occupancy	Exits	Exit Access Corridors	Other Spaces	Mandatory Sprinklers?
Assembly – New < 300 Occupant Load >300 Occupant Load	 A A	 B B	 B C	 No
Educational	A	B	B,C [1]	No
Day Care Centres	A	A	A,B	No
Health Care	A	A, B [2]	A, [2,3]	Yes
Detention	B	B	C	Yes
1 and 2 Family Dwellings Lodging and Rooming Houses	C	C	C	Yes
Hotels and Dormitories	A	B	C	Yes
Apartments	A	B	C	Yes
Residential Board and Care	A	B	B	Yes
Mercantile Class A or B Stores Class C stores	 B C	 B C	 Ceilings: B Walls: C C	No

Business and Ambulatory Healthcare	B	B	C	No
Industrial	B	C	C	No
Storage	B	C	C	No

Notes:

1. Class B are finishes permitted in other spaces. Low height partitions less than 60 in high and not in exit ways are permitted to be lined with Class C finishes.

2. All spaces in this occupancy must be Class A, however surface finishes up to 48 in above floor of Class B finish are acceptable.

3. All spaces in this occupancy must be Class A, however surface finishes in rooms with occupant loads of 4 persons or less are acceptable.

2.4 Wall and Ceiling Regulations by Jurisdiction – Europe

2.4.1 Classification of Lining Materials - Euroclass System

Many of the member countries of the European Union (EU) have adopted the Euroclass rating system for the reaction to fire performance of building products (The Commission of the European Communities, 2000). A complete Euroclass rating comprise 3 parts: the first letter, A1-F, which refer to the contribution to fire (although the non-combustible Class A rating is subdivided into A1 and A2, reflecting the amount of organic material in the product), the droplet rating d0 – d2, which denotes the extent of the formation of flaming droplets, and rating s1-s3, which describes the amount of smoke a material produces. This rating is derived from four tests:

- Non-combustibility test EN ISO 1182 (only applicable to those products rated A1 or A2)
- Gross calorific potential test EN ISO 1716 (only applicable to those products rated A1 or A2)
- Single Burning Item test EN 13823 (only applicable to those products rated to A2-D)
- Ignitability test EN ISO 11925-2 (only applicable to those products rated to B-D)

Table 2.3 summarises the expected performance and example products of the various rating. The highest rating achievable by wood (when treated with fire retardant) is Class B, therefore the Non-combustibility and Gross calorific potential tests are not within the scope of this work.

Table 2.3: Expected performance and example products of Euroclasses, from (The Commission of the European Communities, 2000)

Class	Performance description	Fire scenario and heat attack		Examples of products
A1	No contribution to fire	Fully developed fire in a room	At least 60 kW/m^2	Products of natural stone, concrete, bricks, ceramic, glass, steel and many metallic products
A2	"	"	"	Products similar to those of class A1, including small amounts of organic compounds
B	Very limited contribution to fire	Single burning item in a room	40 kW/m^2 on a limited area	Gypsum boards with different (thin) surface linings Fire retardant wood products
C	Limited contribution to fire	"	"	Phenolic foam, gypsum boards with different surface linings (thicker than in class B)
D	Acceptable contribution to fire	"	"	Wood products with thickness ≥ about 10 mm and density ≥ about 400 kg/m^3 (depending on end use)
E	"	Small flame attack	Flame height of 20 mm	Low density fibreboard, plastic based insulation products
F	No performance requirements	–	–	Products not tested (no requirements)

2.4.1.1 Classification to Single Burning Item test EN 13823

The class rating B to E can largely be derived from the EN 13823 Single Burning Item test as described in Section 2.3.1 and this is the test that is used for classifying wall lining products using the FIGRA, LFS_{EDGE} and THR_{600s} ratings (Table 2.4). There are additional criteria for each class, including performance to EN ISO 11925-2 ignition tests, as well as a classification derived from the amount of smoke produced (s1-s3), and whether or not the sample produces flaming droplets (d0-d3). These are included here for completeness; however, FIGRA is generally the main parameter that decides a material's classification.

Table 2.4: Limits of performance for each Euroclass classification B-E, adapted from (Sundström, 2007).

Class	Test procedure	Classification criteria	Additional Classification
B	EN 13823 and	FIGRA $\leq$ 120 W/s and LFS < edge of the specimen and $THR_{600} \leq$ 7.5 MJ	Smoke production[1] and flaming droplets, particles and/or combinations of these [2]
	EN ISO 11925-2 Exposure = 30s	$F_s \leq$ 150 mm within 60 s	
C	EN 13823 and	FIGRA $\leq$ 250 W/s and LFS < edge of the specimen and $THR_{600} \leq$ 15 MJ	Smoke production[1] and flaming droplets, particles and/or combinations of these[2]
	EN ISO 11925-2	$F_s \leq$ 150 mm within 60 s	
D	EN 13823 and	FIGRA $\leq$ 750 W/s	Smoke production[1] and flaming droplets, particles and/or combinations of these [2]
	EN ISO 11925-2	$F_s \leq$ 150 mm within 60 s	
E	EN ISO 11925-2	$F_s \leq$ 150 mm within 60 s	Smoke production[1] and flaming droplets, particles and/or combinations of these [2]

Notes:

1. *s1=SMOGRA $\leq 30\ m^2/s^2$ and $TSP_{600s} \leq 50\ m^2$,*
   s2=SMOGRA $\leq 180\ m^2/s^2$ and TSP600$\leq 200\ m^2$,
   s3=not s1 or s2.

2. *d0 = No flaming droplets/particles during test.*
   d1 = No flaming droplets/particles persisting longer than 10 seconds,
   d3 = not d1 or d2 (d2 applies to Class E only and requires ignition of the paper in the EN 11925 ignitability test also results in class d2)

While it is not permitted to undertake EN 14390:2007/ISO 9705 room-corner testing to establish a FIGRA Index for a product, Sundström (Sundström, 2007) developed the $FIGRA_{RC}$ or an equivalent FIGRA for the room corner test as would be found in the SBI Test for the same candidate material.

$FIGRA_{RC}$, according to Sundström (2007), is calculated as follows:

$$FIGRA_{RC} = \frac{HRR_{max}}{t_{max}} \qquad [2.6]$$

Where HRR_{max} is the maximum value of the heat release rate (excluding the burner) and t_{max} is the time at which it occurs during the test.

The relationship between the Euroclasses and the performance in the ISO 9705 room (both time to flashover and $FIGRA_{RC}$) is shown graphically in Figure 2.8. Table 2.5 shows that FIGRA Index achieved by each class (from the SBI Test) in comparison to the time to flashover that would be expected in the EN14390/ISO 9705 test.

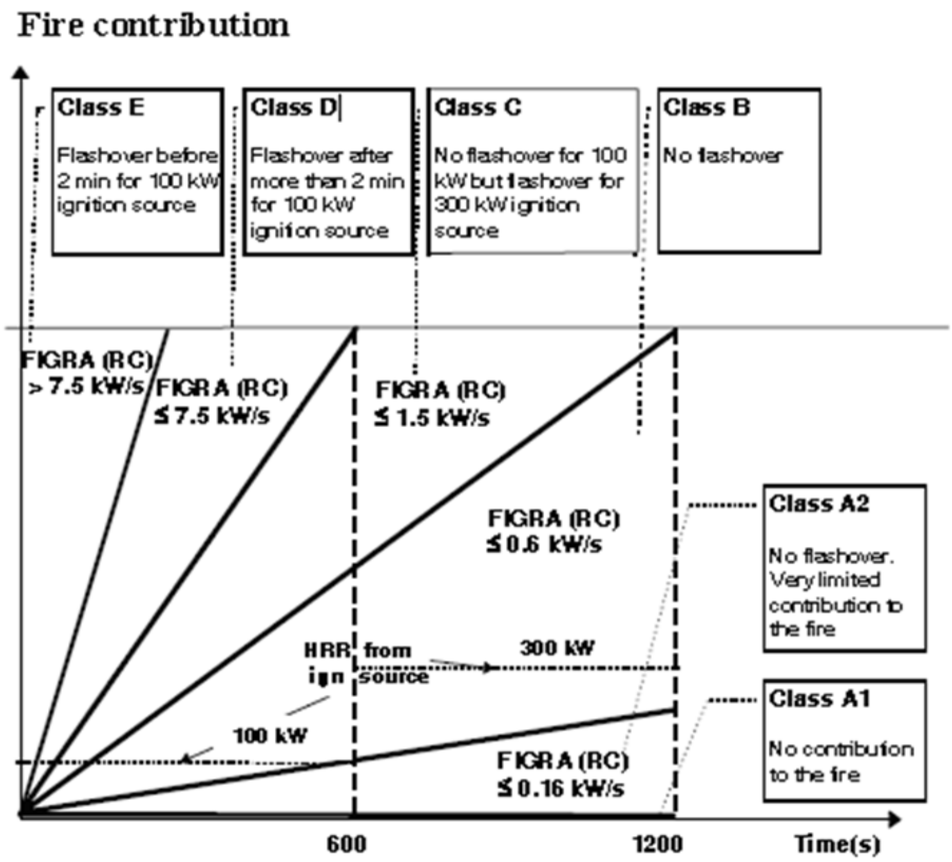

Figure 2.8: Euroclasses compared to the time to flashover in the ISO 9705 test, and the FIGRA value from the ISO 9705 test (Sundström, 2007)

Table 2.5: Time to Flashover by each Euroclass compared to the FIGRA index from the SBI Test, adapted from (Östman & Rydholm, 2002)

Euroclass [in reference test]	FIGRA Index [kW/s] (SBI test)	Time to Flashover (ISO 9705)
A1	Less than 0.15	No flashover
A2	Less than 0.15	No flashover
B	Less than 0.5	No flashover
C	Less than 1.5	Flashover after 10 min
D	Less than 7.5	Flashover 2-10 min
E	More than 7.5	Flashover before 2 min
F	No performance determined	

2.4.1.2 Classification using Single Flame Ignitability Test EN ISO 11925-2

To achieve a Euroclass B-E rating, the lining product must also undergo the Single Flame Ignitability test EN ISO 11925-2 is described in Section 2.3.5. The criteria for passing this test are straightforward:

The test is passed if flame spread does not reach 150 mm beyond the ignition point within the relevant timeframe, and if the paper below the sample is not ignited by flaming droplets.

Two different flame application times and test durations are used depending on the intended Euroclass rating for the material. For class E, the flame application time is 15 seconds, and the test is terminated 20 seconds after the removal of the flame. With a flame application time of 30 seconds for classes B, C and D, the maximum duration of the test is 60 seconds after the removal of the flame.

Ignition of the paper in this test for classes B, C, D or E also results in a d2 flaming droplet rating.

2.4.2 Timber Classification

Classifications for timber include Euroclass B, C, D and E. The EN 13823 Single Burning Item test is in general the governing test for timber products – most timber products achieve a D rating when tested to the EN ISO 13823 SBI Test (Östman & Rydholm, 2002).

Euroclass D and E relate to untreated timber with most timbers with a density of at least 400 kg/m^3 achieving Euroclass D. It is possible for a timber lining to achieve a Euroclass rating without specific testing, by referring to Generic Euroclass (EN 13501-1) values. These generic Euroclass ratings are based on three parameters: an EN product grade reference, minimum product density, and minimum product thickness. Table 2.6 is extracted from Robbins (2014), and shows the generic values for the two latter criteria (the product grade reference varies by product and treatment method). When untreated timber does not achieve the rating needed for application in design, fire retardant impregnation to timber / plywood can elevate timber from Euroclass D (essentially untreated) to Euroclass C or B.

Table 2.6: Generic Timber Euroclass Ratings

Wood-based panel product	EN product grade reference	Minimum density (kg/m^3)	Minimum thickness (mm)	Class
Plywood	EN 636	400	9	D-s2,d0
Solid wood panels	EN 13353	400	12	D-s2,d0
Glued laminated timber	EN 14080	300	40	D-s2,d0

2.4.3 Permitted Locations of Timber Lining Materials

The Euroclass is a reaction to fire classification system only. It was introduced to facilitate the comparison for fire performance of similar products in European countries, to facilitate trade and ensure consistent quality between the products of each member state. The location where each Euroclass rated product is permitted to be used depends on the local building requirements of each member state. For the following jurisdictions: England and Wales, Australia, and New Zealand (although Australia and New Zealand are non-European, the European classes are referred to in both countries as an equivalent to local ratings systems), mapping of the local requirements to the Euroclass equivalent is shown.

2.5 Wall and Ceiling Regulations by Jurisdiction – England and Wales

For England and Wales, the majority of buildings are required to meet "The Building Regulations 2010,' (HM Government, 2010) which outline the requirements which compliant buildings must fulfil and is made under the powers of the Building Act 1984 (HM Government, 1984). Part B of Schedule 1 to the Building Regulations 2000 is that part of UK building legislation which directly deals with surface linings and their contribution to fire, as follows:

*"**Internal fire spread (linings)***

***B2.** (1) To inhibit the spread of fire within the building, the internal linings shall –*

(a) adequately resist the spread of flame over their surfaces; and
(b) have, if ignited, a rate of heat release or a rate of fire growth, which is reasonable in the circumstances.

(2) In this paragraph 'internal linings' mean the materials or products used in lining any partition, wall, ceiling or other internal structure."

There are three guidance documents to demonstrate compliance with the above: Approved Document B (HM Government, 2013), BS 9999:2008 (Anon., 2008) and PD-7974:2003 (Anon., 2003) which provide guidance on ways to comply with the Building Regulations Part B Schedule 1.

2.5.1 Classification of Lining Materials

The classification of lining materials is derived from either the National Class or Euroclass (described in Section 2.5).

2.5.1.1 National Class

The National Class is a rating from Class 0 - Class 4, based on the results from the tests standardised by BS476-7:1987 and, where applicable, BS476-6:1989. Most wall lining products are tested to BS476-7 (described in Section 3.2.3) where they can achieve Class 1 to Class 4 rating based on the extent of flame spread after the sample has been exposed to the irradiance source for 1.5 min, and the extent of flame spread at test completion. The limiting distances for flame spread are shown in Table 2.7.

Table 2.7: Classification of spread of flame according to BS 476-7 (HM Government, 2013)

Classification	**Spread of flame at 1.5 min**	**Final Spread of Flame**
	Limit (mm)	**Limit (mm)**
Class 1	165	165
Class 2	215	455
Class 3	265	710
Class 4	Exceeding the limits for Class 3	

Class 0 refers to products with an extremely low contribution to early fire spread and identified in Building Regulations as requiring:

- a Class 1 surface spread of flame relating to BS 476-7: 1997, and
- An index of performance of not more than 12 and a sub-index 1 of not more than 6 when tested to BS 476-6:1989 (BS 476-6 is described in Section 2.2.3.4).

2.5.1.2 Euroclass

England and Wales are currently member states of the European Union and as are obliged to include the Euroclass as an alternative means of demonstrating the reaction to fire performance of surface linings. Table 2.8 shows the equivalent ratings between the National Class and Euroclass System, which means that those products with a Euroclass rating, are deemed to automatically achieve a National Class rating. However, this "transposition" is unidirectional: the National classifications do not automatically equate with the equivalent classifications. Products with a National Class, therefore, cannot typically assume a European class, unless they have been tested at a minimum to the EN 13823 Single Burning Item test and EN 11925 Single Flame test.

Table 2.8: Equivalent National (England and Wales) and Euroclass ratings

National Class (England and Wales)	**Euroclass**
Non-combustible*	A1 (provision for non-testing)
Limited Combustible*	A2-s3,d2 or better
Class 0	B-s3,d2 or better
Class 1	C, s3,d2 or batter
Class 3	D-s3,d0 or better

**These Classes are not achievable using timber and have not been referred to in this work.*

2.5.2 Timber Classification

2.5.2.1 National Class

When referring to National Class, most untreated timber and wood-based sheet materials achieves a generic rating of Class 3; those with a density of less than 400 kg/m^3 are Class 4 (HM Government, 2013), (which is equivalent to the generic Euroclass ratings). Class 1 performance can be achieved with a wood-based substrate with certain types / products of flame retardant by:

- impregnation treatment
- surface coating applied to a material previously impregnated to Class 1 (to achieve Class 0)
- surface coating treatments alone.

Achieving Class 0 performance by impregnation treatments alone can be achieved, but generally necessitates increased quantities of the chemicals than those necessary for Class 1 (The Timber Research and Development Association, 2003).

2.5.3 Permitted Locations of Timber Linings

2.5.3.1 Approved Document B and BS 9999:2008

Approved Document B is a largely prescriptive design guide for the fire design of buildings, comprising two volumes. Volume 1 refers to private dwelling houses, and is therefore outside the scope of this report, while Volume 2 refers to buildings other than dwelling houses. Outside its scope are health care premises, shopping complexes, assembly buildings, school, buildings containing atria, and others (HM Government, 2013).

BS 9999:2008 – Code of Practice for Fire Safety in the Design, Management and Use of Buildings is a more flexible design guide, which uses a risk-based approach to its guidance and provides design guidance for most building design including the design of those buildings which are not permitted to be designed to Approved Document B, such as atria. (Anon., 2008)

In both documents, the same guidance relating to wall and ceiling linings are provided. Table 2.9 is extracted from section 6, Table 10 of Volume Two of Approved Document B, wherein the permitted wall and ceiling linings are summarised. In Approved Document B, additional guidance for specific internal lining types are referred to in its Section 8, which addresses exposed surfaces in concealed spaces above fire protecting suspended ceilings, as well as in Section 10, which addresses above ground drainage system pipes.

Table 2.9: Permitted Linings Locations from Approved Document B and BS 9999:2008 (HM Government, 2013)

Location	National Class	European Class*
Small rooms of area not more than: a. 4 m^2 in residential accommodation b. 30 m^2 in non-residential accommodation	3	D-s3, d2
Other rooms (including garages)	1	C-s3,d2
Circulation spaces within dwellings		
Other circulation spaces, including the common areas	0	B-s3,d2

**The suffix to the classification "s3, d2"means there is no limit set for smoke production and/or flaming droplets/particles.*

The most stringent requirements for surface finishes are for "circulation spaces" which are defined as "A space (including a protected stairway) mainly used as a means of access between a room and an exit from the building or compartment," which is comparable to the spaces referred to as "exits" in the U.S. or exitways in Australian and New Zealand codes. Paragraph 6.4 also states "Parts of walls in rooms may be of a poorer performance than specified in paragraph 6.1 and Table 10 (but not poorer than Class 3 (National Class) or Class D-s3, d2 (European class), provided the total area of those parts in any one room does not exceed one half of the floor area of the room; and subject to a maximum of 20 m^2 in residential accommodation and 60 m^2 in non-residential accommodation." There appears to be no concessions to these lining requirements when the building is sprinklered.

2.5.3.2 PD-7974-1:2003

PD-7974-1:2003 refers to the first volume of the performance based design guide for fire design in England and Wales (Anon., 2003). There is no specific guidance relating to wall and ceiling linings, however it appears that many designers refer to the guidance provided in the prescriptive documents Approved Document B and BS 9999:2008. PD-7974-1 does include a directive, which states to include the wall linings type when calculating the design fire characteristics to demonstrate that a design meets the performance requirements, although specific data and inputs to design fire calculations are not included (Anon., 2003). Compliance of internal surface linings, even in performance-based design is often shown via adherence to the prescriptive guidance (T Grace, 2016, personal comms.).

2.6 Wall and Ceiling Regulations by Jurisdiction – Canada

2.6.1 Classification of Lining Materials

Linings materials are classified according to CAN/ULC-S102-03. The flame spread characteristics are referred to by the flame spread rating obtained in the test (i.e. there is no classification system beyond the results of CAN/ULCS102-03).

2.6.2 Timber Classification

Appendix D-3 of the NBCC, Division B, (National Research Council Canada, 2010) provides information related to generic flame spread ratings and smoke developed classifications of a variety of building materials (National Research Council Canada, 2010). Information is only provided for generic materials for which extensive fire test data is available (Table 2.10). For instance, lumber (i.e. structural timber), regardless of species, and Douglas fir, Poplar, and Spruce plywood, of thicknesses no less than those listed, are assigned a flame-spread rating of 150.

In general, for wood products up to 25 mm thick, the flame spread rating (FSR) decreases with increasing thickness. Values given in the Appendix D of the NBCC are conservative because they are intended to cover a wide range of materials (Canadian Wood Council, 1996). Specific species and thicknesses may actually have values much lower than those listed in the NBCC Appendix D guidance.

Table 2.10: Generic Flame Spread ratings extracted from Appendix D of the National Building Code of Canada (National Research Council Canada, 2010)

Materials	Minimum Thickness (mm)	Unfinished	Paint or Varnish not more than 1.3 mm Thick, Cellulosic Wallpaper not more than 1 Layer(1)(2)
		FSR	FSR
Gypsum wallboard	9.5	25	25
Lumber	16	150	150
Poplar plywood	11	150	150
Plywood with Spruce face veneer	11	150	150
Douglas fir plywood	6	150	150
Fibreboard low density	11	(4)	150
Hardboard – Type 1	9	150	(4)
Hardboard – Standard	6	150	150

(1) Flame-spread ratings and smoke developed classifications for paints and varnish are not applicable to shellac and lacquer.

(2) Flame-spread ratings and smoke developed classifications for paints apply only to alkyd and latex paints.
(4) Insufficient test information available

In order to demonstrate the variation in timber performance based on species, Table 2.11 shows the test results to CAN/ULC S202.2-07 for 19 mm thick samples of various wood types. The flame spread values for timber are, in most cases, well below 150. While density measurements for this data was not available, it is interesting that some wood species which are typically dense achieved higher flame spread ratings than lower density timbers. For example, the density of white oak in a separate study by the Canadian Wood Council (Alghem, 1984) of 49 white oak trees in the Ontario region was shown range of 600 - 708 kg/m^3 but achieved a higher flame spread rating (100) than Eastern White Pine which has a flam e spread rating of 85 with a density range of measured 237 - 447 kg/m^3 over 128 trees in Ontario region.

Table 2.11: Results for timber linings when tested to CAN/ULC S201 extracted from (Canadian Wood Council, 1996)

Product: Lumber, 19 mm thickness		Flame Spread Ratings
Cedar	Western Red	73
	Pacific Coast Yellow	78
Fir	Amabilis (Pacific Silver)	69
Hemlock	Western	60 – 75
Oak	Red or White	100
Pine	Eastern White	85
	Lodgepole	93
	Ponderosa	100 – 230
	Red	142
	Southern Yellow	130 – 195
	Western White	75
Poplar		170 – 185
Spruce	White	65
	Sitka	74
	Western	100

2.6.3 Permitted Locations of Timber Linings

Paragraph 3.1.13.2. of Division B of the National Building Code of Canada (National Research Council Canada, 2010) states that, "except as otherwise required or permitted by the Subsection, the flame-spread rating of interior wall and ceiling finishes, including glazing and skylights, shall be not more than 150 and shall conform to Table 3.1.13.2.” This means untreated timber is permitted in most areas, since most untreated timber products achieve a flame-spread rating of 150. However Table 3.1.13.2, reproduced as Table 2.12 below, shows the areas where untreated timber is only permitted if the building is sprinklered. Group A, Division 1 occupancies, where untreated timber is permitted provided the area is sprinklered refers to assembly occupancies intended for the production and viewing of the performing arts. Group B spaces, which are the only other spaces where untreated timber is permitted as a wall lining is custodial care, including care/treatment facilities, as well as detention facilities. Interestingly, these two spaces are also the only spaces for which the linings requirements are reduced when sprinklers are included. For all other spaces, including exits or lobbies, untreated timber is not permitted, regardless of whether or not the space is sprinklered.

Table 2.12: Permitted Wall Linings by Area (National Building Code of Canada) (National Research Council Canada, 2010)

Occupancy, Location or Element	**Maximum Flame-Spread Rating for Walls and Ceilings**	
	Sprinklered	**Not Sprinklered**
Group A, Division 1 occupancies, including doors, skylights, glazing and light diffusers and lenses	150	75
Group B occupancies	150	75
Exits	25	25
Lobbies	25	25
Covered vehicular passageways, except for roof assemblies of heavy timber construction in the passageways	25	25
Vertical service spaces	25	25

The National Building Code of Canada (National Research Council Canada, 2010) also permits, in some areas the use of partial wall coverings. Sentence 4 of Paragraph 31.13.2 states that for those spaces that are required to have a flame spread rating of *less than* 150, up to 10% of the total wall area and 10% of the ceiling area is permitted to have a flame spread rating of *not more* than 150 – this means that in these limited areas, materials with a rating of exactly 150 (or better) are permitted. This enables the partial use of untreated timber linings in these spaces. Furthermore, corridors are ordinarily permitted a maximum flame spread rating of 75 (i.e. no untreated timber), however, it is permissible to include products with a flame spread rating of 150 or less (i.e. including uncoated timber) on the lower half of the wall, provided that the product used on the upper half of the wall has a flame-spread rating of no greater than 25.

2.7 Wall and Ceiling Regulations by Jurisdiction – Australia

The Building Code of Australia (BCA) consists of Volumes One and Two of the National Construction Code (NCC) (Australian Government , 2015) The BCA is produced and maintained by the Australian Building Codes Board (ABCB) on behalf of the Australian Government and State and Territory Governments. The BCA has been given the status of building regulation by all States and Territories.

For commercial buildings, Volume One of the National Construction Code is the relevant document. Section C describes the Objectives. CP4 is the performance objective which is directly applicable to surface linings, and it states:

CP4

To maintain tenable conditions during occupant evacuation, a material and an assembly must, to the degree necessary, resist the spread of fire and limit the generation of smoke and heat, and any toxic gases likely to be produced, appropriate to—

(a) the evacuation time; and

(b) the number, mobility and other characteristics of occupants; and

(c) the function or use of the building; and

(d) any active fire safety systems installed in the building.

2.7.1 Classification of Lining Materials

The prescriptive guidance for the linings which will meet the performance criteria is Volume 1 of the National Construction Code of Australia (Australian Government , 2015).Wall and ceiling linings are divided into Group Numbers 1-3. The Group Number is derived from the ISO 9705:1993 full scale test, and depends primarily on the time to flashover, wherein

Group 1: No flashover point reached during the length of the test.

Group 2: Flashover point reached between 10 and 20 min

Group 3: Flashover point reached between 2 and 10 min

It is important to note that, unlike other national codes, the Australian NCC Clause 1.10 (b) excludes the use of fire-retardant coatings to comply with fire hazard properties. While the reasoning for this exclusion is not stated in the legislation, it is believed that the reason for the prohibition of the use of paint or fire retardant coatings to meet Group Number requirements is that this coating is susceptible to damage/wear over time. According to the National Construction Code Guide 2015 (Australian Government, 2015), the exclusion of fire retardant coatings does not prohibit the use of impregnated fire retardants to achieve the necessary Group Numbers.

Group Numbers can also be derived from the AS 3837 cone calorimeter test which has been correlated with the ISO 9705 test. The method of correlation is similar to the New Zealand method, which is discussed in Section 2.8.1 of this work.

2.7.2 Timber Classification

While generic ratings are not available in the Australian design guidance, Warrington Fire Research undertook testing to AS 3837:1998 of 40 samples of untreated timber wall linings used in Australia, including Ash, Blackbutt and Jarrah species, all of which were found to achieve Group Number 3 (Warrington Fire Research, 2010).

2.7.3 Permitted Locations of Timber Linings

Table 2.13 is adapted from Volume 1 of the National Construction Code of Australia (Australian Government , 2015), and shows the permitted wall linings for each space within each type of publicly occupied buildings (private homes and private dwellings within public buildings are excluded). Since untreated timber has been shown to generally achieve Group 3, the spaces where Group 3 linings are permitted are the only areas where untreated timber can be used as linings, and these are highlighted in greyscale.

Table 2.13: Permitted wall and ceiling surface linings in Australia by Occupancy, adapted from the National Construction Code (2015)

Suppression System	Fire Isolated Exits Wall/Ceiling	Public Corridors		Specific Areas		Other Areas Wall/Ceiling
		Wall	Ceiling	Wall	Ceiling	
Class 2 – containing 2 or more sole-occupancy units each being a separate dwelling. Class 3 - a residential building which is a common place of long term or transient living for a number of unrelated persons, excluding accommodation for the aged, people with disabilities, and children						
Unsprinklered	1	1,2	1,2	1,2,3	1,2,3	1,2,3
Sprinklered	1	1,2,3	1,2,3	1,2,3	1,2,3	1,2,3
Class 3, Accommodation for the aged, people with disabilities, and children Class 9a health-care building, including those parts of the building set aside as a laboratory						
Unsprinklered	1	1	1	1,2	1,2	1,2,3
Sprinklered	1	1,2	1,2	1,2,3	1,2,3	1,2,3
Class 5 - office building used for professional or commercial purposes Class 6 - A shop or other building for the sale of goods by retail or the supply of services direct						

to the public, including an eating room, or a dining room, bar area , a hairdresser's or barber's, showroom, or service station Class 7 – Carpark or storage or display of goods or produce for sale by wholesale. Class 8 - a laboratory, or a building in which a process for the production, of goods or produce is carried on for trade, sale, or gain Class 9b schools - an assembly building, including a trade workshop, laboratory in a primary or secondary school, but excluding any other parts of the building						
Unsprinklered	1	1,2	1,2	1,2,3	1,2	1,2,3
Sprinklered	1	1,2,3	1,2,3	1,2,3	1,2,3	1,2,3
Class 9b other than schools - an assembly building, including a trade workshop, laboratory						
Unsprinklered	1	1	1	1,2	1,2	1,2,3
Sprinklered	1	1,2	1,2	1,2,3	1,2,3	1,2,3
Class 9c –An aged –care building						
Sprinklered	1	1,2	1,2	1,2,3	1,2,3	1,2,3

"Specific Areas" refers to:

(a) For Class 2 and 3 buildings, a sole-occupancy unit

(b) for Class 5 buildings, open plan offices with a minimum floor dimension/floor to ceiling height ratio > 5; and

(c) for Class 6 buildings, shops or other building with a minimum floor dimension/floor to ceiling height ratio > 5; and

(d) for Class 9a health-care buildings, patient care areas; and

(e) for Class 9b theatres and halls, etc, an auditorium; and

(f) for Class 9b schools, a classroom; and

(g) for Class 9c buildings, resident use areas.

Since untreated timber has been found to have a Group Number of 3 in most cases, they are permitted in most places in unsprinklered buildings. Class 9a (health care facilities) and some 9b (other education facilities) have the most stringent requirements, with timber only permitted in "specific areas". It must be noted that for commercial facilities Class 5 – 9b Schools, the ceiling of shops, classrooms, and auditoriums is not permitted to include untreated timber linings, whereas these are acceptable on the walls in the same spaces. The Australian Fire Code Reform Centre in 1996 (Dowling & Caird Ramsay, 1996) undertook a study into the fire performance of wall and ceiling linings in order to make recommendations regarding regulatory control of wall and ceiling linings for fire safety, and provide the basis for the Group Number system. This study, using Australian Fire Incident reporting data found that, although data was limited, fires in buildings appeared to be more likely to spread beyond the room of origin (generally resulting in poorer fire safety outcomes), when the room of origin included combustible ceilings. The final report on this study cited the Summerland Leisure Complex fire, on the Isle of Man where 50 people were killed in a fire in an auditorium where the most rapid flame spread occurred across a ceiling comprising acrylic sheets, demonstrating the tendency for fire to spread rapidly across ceilings, where the heat is concentrated (Dowling & Blackmore, 1998).

The specific areas for Class 5 and 6 buildings depend on the minimum floor dimension/floor to ceiling height ratio of > 5. A ratio of >5 does not allow the use of ceiling timber linings – that is, a space with low ceilings compared to floor area (such as an open plan office with a low ceiling) must have more stringent linings requirements.

2.8 Wall and Ceiling Regulations by Jurisdiction – New Zealand

In New Zealand, all building work must comply with the New Zealand Building Code (NZBC) which is contained in Schedule 1 of the Building Regulations 1992 (New Zealand Government, 2012).

The Building Code comprises:

1. Objectives - which are the social objectives from the Building Act)
2. Functional requirements - which are the functions or roles that the building must perform to meet the Objectives
3. Performance criteria - which are the performance criteria the building must achieve. By meeting the performance criteria, the Objective and Functional requirement can be achieved.

Prior to 2012, the NZBC clause regarding interior linings for fire (Clause C3.3.1) comprised a performance requirement as follows: "Interior surface finishes on walls, floors, ceilings and suspended building elements, shall resist the spread of fire and limit the generation of toxic gases, smoke and heat, to a degree appropriate to (a) the travel distance, (b) the number of occupants, (c) the fire hazard, and (d) the active fire safety systems installed in the building (New Zealand Government, 1992). The deemed-to-comply compliance document of the time, the so-called C/AS1 (New Zealand Government, 2001), required that products were tested to the small scale test AS/NZS 1530 Part 3 (Anon., 1999). This test places a 450 mm x 600mm vertical sample of material opposite a gas-fired radiant panel. The sample is moved toward the radiant panel during the test and measurements are made of ignition time, radiation (from the face of the sample) and smoke optical density. These measurements are used to calculate a Spread of Flame index and a Smoke Developed index. C/AS1 referred to these indices when controlling the performance of linings in a space (New Zealand Government, 2001).

The AS/NZS 1530.3 test was a convenient, low-cost small scale test. However, it had limited correlation with real-sized enclosures, making it an arbitrary measure of lining performance. Gardner and Thompson (1988) found no correlation between the flashover time in a room fire test and the flame spread index from AS 1530.3. The Fire Code Reform Centre (FCRC, 1998) also found that some materials that are known to ignite and burn when exposed to a gas burner in a room corner did not ignite in the AS/NZS 1530.3 test. There was also variation in the levels of impressed radiation during the test and smoke emission measurements were inconsistent.

In 2012 the Building Code was changed and the AS/NZS 1530.3 test method was replaced. The fire safety objectives of the Building Code are largely similar in both editions and are not repeated here. However, the performance criteria of C3.3.1 was largely replaced by the performance criteria of Clause C3.4a in limiting the use of interior lining products. But rather than providing a qualitative requirement for lining performance, C3.4a quantitatively specified the required performance of linings to using a system of Group Numbers which are allocated based on a full-scale room fire-corner test to ISO 9705 (New Zealand Government, 2012) (see Section 2.8.1). The deemed-to-comply Acceptable Solution subsequently included provision for testing to ISO 5660 (small-scale) results. These results were required to be post-processed to provide a prediction of how the material would have performed in the ISO 9705 test (New Zealand Government, 2012). Finally, in April 2015 additional test options for determining a Group Number based on European fire test methods were introduced (Ministry of Building, Innovation and Employment, 2015). This enabled the use of imported products as well as an alternative compliance pathway for local products which had already undergone Euroclass testing.

The advantages of the revised surface lining requirements were that the test correlated better with full scale enclosures, providing more realistic linings guidance. Furthermore, the Group Number system was more consistent with the regulations of trade partners and there was a more consistent framework to show compliance.

2.8.1 Classification of Lining Materials

New Zealand uses a Group rating system which similar to the Australian Group rating, and is based on the ISO 9705:1993 test where (New Zealand Government, 2012):

Group 1: No flashover point reached during the length of the test.
Group 2: Flashover point reached between 10 and 20 min
Group 3: Flashover point reached between 2 and 10 min
Group 4: Flashover point occurs before 2 min

The S-suffix refers to the amount of smoke that the lining product is expected to produce. Those products whose Group Number includes an S-suffix produce less smoke than the equivalent Group Number without the suffix. Group 1-S means that during the ISO 9705 test the average smoke production rate over the period 0–20 min was no greater than 5.0 m^2/s. Group 2-S means that during the ISO 9705 test the average smoke production rate over the period 0–10 min was no greater than 5.0 m^2/s.

The deemed-to-comply New Zealand Acceptable Solutions permits Group Numbers to be found using by testing to ISO 5660-1:2002 (New Zealand Government, 2012). This method requires that in addition to meeting the general requirements of ISO 5660-1:2002, as well as testing the sample under the following conditions:

i, An applied external heat flux of 50 kW/m^2

ii, A test duration of 15 min

iii, The total heat release measured from start of the test

iv, horizontally oriented sample

v, Ignititon initiated by the external spark igniter.

Time versus heat release rate data, (including the time to ignition defined as the time when the heat release rate reaches or first exceeds 50 kW/m^2) must be collected for three replicate specimens, and for each specimen, the Ignitability Index (I_{IG}) can be found in reciprocal min:

$$I_{IG} = \frac{60}{t_{ig}} \qquad [2.7]$$

Two heat release rate indices, which are the definite integral expressions representing the area under a heat release rate $\ddot{q}(t)$curve from the ignition time (t_{ig}) until the end of the test (t_f):

$$IQ_1 = \int_{t_{ig}}^{t_f} \left[\frac{\ddot{q}(t)}{\left(t - t_{ig}\right)^{0.34}} \right] dt \qquad [2.8]$$

$$IQ_{12} = \int_{t_{ig}}^{t_f} \left[\frac{\ddot{q}(t)}{\left(t - t_{ig}\right)^{0.93}} \right] dt \qquad [2.9]$$

Lastly, the three integral limits are found as follows:

$$IQ_{,10\,min} = 6800 - 540 I_{ig} \qquad [2.10]$$

$$IQ_{,2\,min} = 2475 - 165 I_{ig}$$

$$IQ_{,12\,min} = 1650 - 165 I_{ig}$$

The integral limits are used to classify the materials, when compared with the heat release rate indices:

i) If $IQ_1 > IQ_{10min}$ and $IQ_2 > IQ_{2min}$, the material is a Group Number 4 material

ii) If $IQ_1 > IQ_{10min}$ and $IQ_2 \leq IQ_{2min}$, the material is a Group Number 3 material

iii) If $IQ_1 \leq IQ_{10min}$ and $IQ_2 > IQ_{12min}$, the material is a Group Number 2 material

iv) If $IQ_1 \leq IQ_{10min}$ and $IQ_2 \leq IQ_{12min}$, the material is a Group Number 1 material, or

v) If the ignition criterion in Step 1 above is not reached, the material is a Group Number 1 material.

The test and analysis is to be repeated for each replicate specimen tested. If a different classification group is obtained for different specimens tested, then the highest (worst) classification for any specimen must be taken as the final classification for that material.

In general, this method provides good correlation between the ISO 5660-1:2002 test and the ISO 9705:2003 test. Collier et al (2006) undertook a study of 8 different materials tested to ISO 5660-1:2002, ISO 9705 and found that all materials tested to ISO 5660-1:2002 achieved the same or more conservative classification than the same material in the ISO 9705 test. Four products achieved a more conservative rating in the ISO 5660 test, three of which were polymers, and the remaining product was plywood treated with two coats of intumescent which achieved Group 3 in the ISO 5660 test, and Group 2 in the ISO 9705 test.

Both New Zealand and Australia refer to the ISO 9705 test as the reference test for evaluating the fire performance of linings. However, while NZ refers to the ISO 5660 test as a small scale alternative, Australia refers to AS 3837. Both tests utilise the cone calorimeter, with the sample located in the horizontal position and exposed to an irradiance of 50 kW/m^2. However the fundamental differences between these two methods (see Section 2.2.3) arise the end of test criteria, as described in Section 2.2.3. The differences in end of test criteria means that for materials which fail to ignite properly and/or for which the mass loss rate drops below 150 g/m^2 (averaged over one minute) the classification results to AS3837:1998 can be less conservative than those achieved using the ISO 5660-1:2002.

Collier et al. (2006) tested 9 mm plywood with one coat of undercoat and two coats of intumescent paint in accordance with AS 3837:1998, and found that the end of test was deemed to have occurred at 84 seconds after the mass loss rate was less to be less 150 g/m^2 when averaged over one minute, thus allocating the sample as a Group 1. However when tested using ISO 5660-1:2002 end of test criteria, the sample achieved a more conservative Group 3 rating. Similarly when synthetic rubber was tested as part of the same study, the test achieved the AS 3837:1998end of test criterion for mass loss rate at 159 seconds on the basis that the mass loss rate was less than 150 g/m^2 when averaged over one minute. The test was allowed to continue beyond this point, however, and the rubber continued to burn at a rate just below that level for a period exceed 400 seconds (Collier, Whiting, & Wade, 2006), therefore the classification that this would have achieved was less onerous than would have been received when tested to ISO 5660-1:2002.

2.8.2 Timber Classification

Appendix A1.3 to the C/VM2 guidance document provides the correlation for achieving Group Number based on the ISO9705:1993 test, while Appendix A1.5 to the C/VM2 provides generic ratings for linings products (New Zealand Government, 2014). Solid wood or wood products can be accepted as achieving Group Number 3 without specific testing, provided that the wood lining is no less than 9.0 mm thick, with a density greater than or equal to 400 kg/m^3 (or 600 kg/m^3 if the product is a particle board), and any paint or stain applied to is no thicker than 0.4 mm, and is applied such that it achieves 100 g/m^2 or less. This generic rating was derived mostly from a study by Collier et. al (2006) which found that exposed timber linings (with no retardant treatment) have been found to generally achieve Group 3 rating.

2.8.3 Permitted Locations of Timber Linings

Building work in New Zealand is regulated and must comply with Schedule 1 of the 1992 Building Regulations Act, otherwise referred to as the Building Code of New Zealand (NZBC). Clause C of this Code relates to fire design, and includes performance criteria, which are *"qualitative or quantitative criteria with which buildings must comply in their intended use."* The performance requirement relevant to surface linings is Clause 3.4. Clause 3.4 is unusual when compared to other requirements in the New Zealand Building Code as this clause includes strict quantitative performance requirements, and does not allow for specific engineering. Clause 3.4(a) tabulates the requirements for wall and ceiling linings (Table 2.14).

Table 2.14: Requirements of NZBC Clause 3.4 (a) replicated from (New Zealand Government, 2012)

Area of building		**Performance determined under conditions described in ISO9705:1993**
	Buildings not protected with an automatic fire sprinkler system	**Buildings protected with an automatic fire sprinkler system**
Wall/ceiling materials in sleeping areas where care or detention is provided	Material Group Number 1-S	Material Group Number 1 or 2
Wall/ceiling materials in exitways	Material Group Number 1-S	Material Group Number 1 or 2
Wall/ceiling materials in all occupied spaces in importance level 4 buildings	Material Group Number 1-S	Material Group Number 1 or 2
Internal surfaces of ducts for HVAC systems	Material Group Number 1-S	Material Group Number 1 or 2
Ceiling materials in crowd and sleeping uses except household units and where care or detention is provided	Material Group Number 1-S or 2-S	Material Group Number 1 or 2
Wall materials in crowd and sleeping uses except household units and where care or detention is provided	Material Group Number 1-S or 2-S	Material Group Number 1, 2, or 3

Wall/ceiling materials in occupied spaces in all other locations in buildings, including household units	Material Group Number 1, 2, or 3	Material Group Number 1, 2, or 3
External surfaces of ducts for HVAC systems	Material Group Number 1, 2, or 3	Material Group Number 1, 2, or 3
Acoustic treatment and pipe insulation within airhandling plenums in sleeping uses	Material Group Number 1, 2, or 3	Material Group Number 1, 2, or 3

Clause C3.4 does not apply to detached dwellings, within household units in multi-unit dwellings, or outbuildings and ancillary buildings.

New Zealand Building guidance includes two design pathways, with their respective documentation: 1, the Acceptable Solutions, which is a suite of prescriptive guidance for building design based on building use, and 2, the C/VM2 – Protection from Fire Verification Method, which is a performance based design framework which provides inputs to fire models used in design verification. Both the Verification Method and Acceptable Solutions define exitway as "All parts of an escape route protected by fire or smoke separations, or by distance when exposed to open air, and terminating at a final exit." (New Zealand Government, 2012). However, there is no absolute definition of "crowd" space. The closest "definition" which is commonly referred to can be found in Schedule 2 of the Building Act which divides crowd uses into four categories, and includes retail shops and educational facilities:

Table 2.15: Uses related to crowd activities in the New Zealand Building Code (New Zealand Government, 2005)

Uses related to crowd activities

Use	*Spaces or dwellings*	*Examples*
CS (Crowd Small)	enclosed spaces (without kitchens or cooking facilities) where 100 or fewer people gather for participating in activities	cinemas (with qualifying spaces), art galleries, auditoria, bowling alleys, churches, clubs (non-residential), community halls, court rooms, dance halls, day-care centres, gymnasia, lecture halls, museums, eating places (excluding kitchens), taverns, enclosed grandstands, indoor swimming pools
CL (Crowd Large)	enclosed spaces (with or without kitchens or cooking facilities) where more than 100 people gather for participating in activities, but also enclosed spaces with kitchens or cooking facilities and where 100 or fewer people gather for participating in activities	cinemas (with qualifying spaces), schools, colleges, and tertiary institutions, libraries, night-clubs, restaurants and eating places with cooking facilities, theatre stages, opera houses, television studios (with audience)
CO (Crowd Open)	spaces (other than those below a grandstand) for viewing open air activities	open grandstands, roofed but unenclosed grandstands, or uncovered fixed seating
CM (Crowd Medium)	spaces for displaying or selling retail goods, wares, or merchandise	exhibition halls, retail shops, supermarkets, or other stores with bulk storage or display

Since the requirements for surface linings are enshrined in the NZ legislation, not the design guidance, both the Acceptable Solution suite of documents and the C/VM2 reflect the rules regarding surface finishes outlined in the New Zealand Building Code. However, the Acceptable Solutions include some concessions to these rules. Those relevant to timber are repeated as follows (New Zealand Government, 2012):

a*) Small areas of non-conforming product within a firecell with a total aggregate surface area not more than 5.0 m²*.

b) Handrails and general decorative trim of any material such as architraves, skirtings and window components, including reveals, provided these do not exceed 5% of the surface area of the wall or ceiling they are part of.

c) Timber joinery and structural timber building elements constructed from solid wood, glulam or laminated veneer lumber. This includes heavy timber columns, beams, portals and shear walls not more than 3.0 m wide, but does not include exposed timber panels or permanent formwork on the underside of floor/ceiling systems.

d) Individual doorsets.

e) Continuous areas of permanently installed openable wall partitions having a surface area of not more than 25% of the divided room floor area or 5.0 m2, whichever is less, and,

f) Marae buildings using traditional Maori construction materials (eg, tukutuku and toetoe panels), include for Crowd Spaces (which includes educational facilities).

Furthermore, in educational facilities, a further exemption is permitted wherein materials of Group Number 3 are permitted on surfaces less than 1.2 m above floor level in firecells containing classrooms, passageways and corridors of educational buildings. It is intended to allow for materials such as painted particleboard to be used from floor level to a height of 1.2 m where rapid escape is possible. This exemption only applies to those firecells which have (New Zealand Government, 2012):

i. *An occupant load of less than 250,*
ii. *The fire cells are at ground floor level and are served by at least two exitways or final exits,*
iii. *The material Group Number is no more than 2–S for surfaces 1.2 m or more above floor level.*

Even with the above concessions, the specificity of the new performance requirement clause, coupled with the broad definition of "crowd" means that many spaces are prohibited from including untreated timber as linings greater than 5 m². There is little scope for performance-based design of surface linings, as this is a legislative requirement in the Building Act, not a specification from any kind of design guidance as is the case in other jurisdictions such as Australia. This restriction has required some designers to alter their preferred products which were previously more acceptable, for example, linings which comprise of timber panels are popular as dado walls in public spaces for their durability and appearance but these are no longer acceptable in crowd use spaces. Practical exceptions to this requirement are given in the compliance documents for timber joinery, trim, heavy structural timber members and small areas of non-conforming product (< 5m² in area) (New Zealand Government, 2012).

'Problematically, these exceptions were made for practical reasons rather than to minimise fire risk. Their effect on fire safety is not readily quantifiable from existing surface linings fire performance data

It is important to note that prior to 2012, exposed timber was also not generally permitted in these spaces when tested to AS 1530.5. However, as this was a deemed-to-comply test, it was possible to identify alternative means of showing compliance. In some cases, these alternative methods permitted the inclusion of bare timber, although consistent verification of compliance was difficult to achieve. Post-2012, compliance with the Group 3 specifications for crowd spaces are now obligatory to comply with the New Zealand Building Code (New Zealand Government, 2012).

2.9 Summary of Findings

Table 2.16 summarises where in a building each jurisdiction permits the installation of bare timber when considering its contribution to fire development. This table describes the use of spaces using the reference terms (such as Crowd or Sleeping use) as used in the New Zealand Building Code in order to facilitate comparison with the New Zealand situation especially. Furthermore, the New Zealand definitions are broad, and can encompass multiple occupant descriptors that are used in other jurisdictions. For a further summary of permitted surface linings by jurisdiction, with greater delineation between the uses of spaces (particularly, more division of the New Zealand terms "crowd spaces" and "other spaces") see Table A1 in Appendix A.

The key findings from this review of code requirements for internal linings are as follows:

1. Large scale fire tests such as NFPA 286 and ISO 9705 are conceptually similar, whereas small scale fire tests vary considerably in their approach to predicting the flame spread performance of wall and ceiling linings. For example, the ASTM E-84 test, and Single Burning Item test measures actual flame spread whereas those tests using the cone calorimeter derive their performance ratings for flame spread from ignition time and analysis of the heat release rate against time during the test.

2. Most jurisdictions have the most stringent wall and ceiling lining requirements in exitways and escape routes.

3. Occupant load, the presence of sprinklers, the degree of independence of occupants, and relative location to final exits are the factors generally considered across jurisdictions when limiting wall and ceiling surface finishes. Floor area is a consideration in the U.S.A., (NFPA only), Australia, and the U.K and is usually referred to when applying exemptions to surface finish requirements. Australia is the only country out of those surveyed to formally include ceiling height as a factor used when limiting surface finishes in specific areas.

4. In general, walls and ceiling are treated equivalently, that is, the ratings for walls and ceiling are identical within the same space. However, New Zealand, Australia and the U.S.A. (NFPA) permit less stringent wall surface finishes than ceiling finishes in some crowd spaces (and in New Zealand, in some non-custodial sleeping areas).

5. The consideration, within prescriptive design, of partial wall linings is rare in the jurisdictions surveyed here – Canada makes the most allowance for partial wall and ceiling linings in public buildings with New Zealand permitting some partial wall linings in education facilities.

6. With the exception of England and Wales, most jurisdictions allow concessions to wall/ceiling lining requirements for sprinklered buildings, although it is difficult to compare the magnitude of each jurisdiction's concession as each rating system varies.

7. New Zealand, Australia, England and Wales, sleeping (i.e. residential but not household units) occupancies have broad, strict controls on the acceptable wall linings in rooms and corridors and do not permit bare timber in these spaces (except in England and Wales, in rooms of areas less than 4 m^2). The U.S.A. (NFPA) and Canada separate sleeping areas into more categories, dependent on occupant load and permanent of occupants, and permitted uncoated timber in those sleeping areas with permanent, or semi-permanent occupants.

Table 2.16: Summary table of the treatment of timber in various jurisdictions

		Jurisdiction				
Space	**Suppression**	**NZ**	**Australia**	**England**	**Canada**	**U.S.**
Sleeping Uses where care or detention is provided	**Unsprinklered**	No bare timber linings	Bare timber linings permitted except in corridors, patient-care, or sole occupancy rooms	No bare timber linings except in rooms of less than 4 m^2 floor area	No bare timber linings	No bare timber linings.
	Sprinklered		Bare timber linings permitted except in corridors		Bare timber linings permitted except corridors or exitways	
Exitways	**Unsprinklered**	Bare timber linings are not permitted in exitways in any occupancy in any jurisdiction				
	Sprinklered					
Crowd uses	**Unsprinklered**	No bare timber linings	Bare timber linings are permitted, except in public corridors, and on the ceilings of low-ceiling classrooms, shops or offices.	No bare timber linings except in rooms of less than 30 m^2 floor area	Bare timber is permitted except in unsprinklered corridors and in unsprinklered performing arts spaces	Depends on Use Group: Bare timber is generally permitted in sprinklered spaces, as well as unsprinklered assembly spaces with < 300 people, unsprinklered business spaces, and some unsprinklered mercantile spaces
	Sprinklered	Walls only	Bare timber linings are permitted			
Sleeping Uses without care or detention	**Unsprinklered**	No bare timber linings	Bare timber linings permitted except in corridors.	No bare timber linings except in rooms of less than 4 m^2 floor area	Bare timber linings permitted	N/A
	Sprinklered	Walls only	Bare timber linings permitted	No bare timber linings except in rooms of less than 4 m^2 floor area		Bare timber linings permitted
Other spaces		Bare timber permitted				Depends on Use Group

3. Background to Flame Spread Modelling

3.1 Flame Spread Theory – Overview

Understanding flame spread theory and how it relates to interior linings is important in order to understand how interior lining choice and layout affects the fire growth and tenability conditions in a compartment.

Flame spread can refer to two broad concepts: either the moving flame phenomenon in close proximity to the source of its fuel originating from a solid or liquid phase, or flame propagation in premixed fuel and air systems. The study is concerned with flame spread on solid timber, therefore the first description more aptly represents the "flame spread" referred to in this thesis.

Once ignition of a liquid or solid fuel has taken place where combustion and flaming is established, flame spread across the surface of the fuel, or "the extension of the burning area" (Quintiere , 1998) is the next stage which contributes to fire growth. While models for flame spread vary significantly, it is generally accepted that in order for burning to continue and flames to spread on solid fuels, fuel must be pyrolysed ahead of the flame front. Hasemi (2016) considers flame spread as a series of consecutive ignitions, and describes this flame spread process in four steps:

1. Vaporisation of solids or liquids due to the heating by flames over the fuel's surface.
2. Mixing of the pyrolysed gas and oxygen close to the fuel surface.
3. Combustion of the pyrolysed gas and oxygen and formation of the diffusion flame.
4. Heating of the unburnt fuel surface to ignition temperature from the diffusion flame.

Hasemi adds that the oxygen and fuel concentrations, as well as the heat transfer from the flame and solid have a significant effect on the rate of the flame spread process. The balance between Steps 4 and 1 in the above cycle largely dictates the rate of flame spread i.e. the rate that flames can transfer heat to the unburnt surface (Step 4) dictates the rate at which the surface vaporises when heated. With this in mind, flame spread can be accelerated by increasing the efficiency of heat transfer from the flames to the unburned surface. Heat transfer from the flames to the unburnt surface ahead of the flame front is directly affected by gravity, by wind effects, or the mean air flow, affecting the flames. Flame spread is assisted by the wind effects when the flame spread is in the direction of the mean air flow, resulting in "wind-aided" or concurrent spread. Alternatively, flame spread in the direction opposite to the air flow direction is referred to as "opposed" flow. In either case, the air flow can be natural (caused by buoyancy) or forced (caused by an external input, such as wind or a fan).

In compartment fires, flame spread can occur on the interior linings of the space. Upward flame spread on walls (Figure 2.1 (b)) , as well as lateral flame spread on ceilings (Figure 2.1(c)) are both wind-aided flame spread examples, while opposed spread can be observed across a combustible floors, or downward spread along walls from a burning ceiling or upper wall

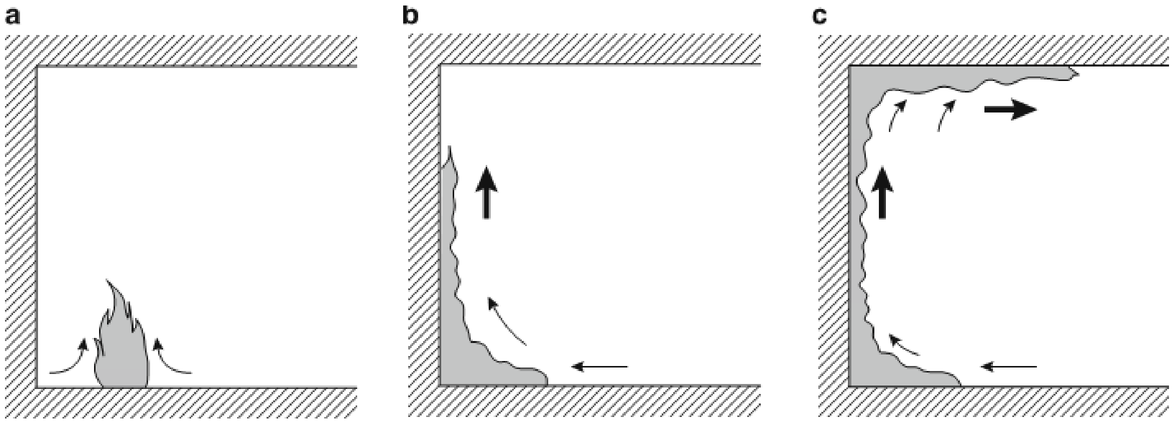

Figure 3.1: Flame spread directions in a compartment fire with combustible linings (Hasemi, 2016)

Hasemi identifies wind-aided flame spread as the more significant contributor to fire hazard in an enclosure fire. Wind-aided spread is more hazardous than opposed flame spread, as wind-aided spread is usually more rapid, and as flames spread, more heat is generated to increase the cycle of successive ignitions, further accelerating flame spread. In fact Alpert and Ward (Alpert & Ward, 1984) noted that the spread of flame up a vertical surface accelerates exponentially. Drysdale (Drysdale, 1994) adds that the hazard of wind-aided spread increases as it travels across the room, in particularly, across a combustible ceiling, as the rapid moving flames have the potential to ignite other room contents, and further feed fire development.

Factors which affect the rate of wind-aided flame spread on solids include the time to local burnout, when the heat release rate of a portion of surface begins to decrease as all the fuel is consumed, and the time to ignition. If the burnout time is large compared to the time of ignition for the surface (i.e the fuel behind the pyrolysis front begins to burnout before the next area is adequately pyrolysed and begun to ignite), then flame spread is slow, and difficult to sustain. Time to burn out and time to ignition are not solely material properties; these are affected by ambient temperatures and any pre-heating of the surface. Interestingly, grooves and roughness of a surface (such as the effects of wood grain) can also affect its flame spread rate, as this affects entrainment into the flame front, which affects the length of the flame and its proximity to the unburnt surface (Hasemi, 2016) .

Opposed flow, on the other hand, is much less dependent on pre-heating or flame length, as the flame heats a much smaller area ahead of the flame front. The dominant mode of heat transfer driving opposed flow flame spread is conduction, either through the gas or solid phases. The thermal thickness, as well as the material properties of the solid are more important factors affecting the rate of opposed flow flame spread than in wind-aided spread. For a thermally thin solid, i.e. a solid where there is no temperature gradient between its two opposite side, the rate of flame spread has been repeatedly shown to be inversely proportional to the thickness of the material. Parker (Parker, 1972) in his study of flame spread on cellulosic materials where he measured the downward flame spread on thin cardboard, describes downward flame spread as being determined by the rate of conductive heat transfer through the gas phase from the leading edge of the flame to the unaffected fuel for thermally thin fuels. Royal (Royal, 1970) describes the limiting thicknesses for a cellulosic fuel such as wood to be 0.2 mm -1.55 mm, while Quintiere (Quintiere, 1998) prescribes a general upper limit of 2 mm before a material is thermally thick. For thermally thick solids, the rate of conductive heat transfer through the solid to unburned fuel is more important than heat transfer through the gas phase, therefore the thermal conductivity of the solid becomes a dominant factor in the rates of downward spread which the solid will support. For both thermally thin and thermally thick fuels, the density and heat capacity are also relevant as these affect the rate at which the fuel pyrolyses (Drysdale, 1994).

Lastly, the majority of flame spread studies seek to identify the key factors affecting flame spread take place using isolated samples in controlled conditions. However, Drysdale notes that in real fires, exposure to radiant heat enhances the rate of flame spread considerably. The enhancement effect of radiation on flame spread is observable, for example, in room fire where flame spread is accelerated in the corners due to reflected heat from opposing walls (Drysdale, 1994). Delichatsios et al. (1994) measured the rates of two 0.64 wide by 2.4 m tall plywood samples exposed to external radiation of 4 kW/m^2 - 11 kW/m^2 and ignited by a hot wire. In the test with the highest external flux (11 kW), flames reached the top of the 2.4 m sample approximately 175 s earlier than in the test where the external heat flux was 4.8 kW/m^2. However, most radiation research and flame spread models investigate the effect of radiation on ignition of samples, and not specifically on the direct dependence of flame spread rates on radiation, so there is little further quantitative information available (Drysdale, 1994) .

Table 3.1: Factors affecting the rate of flame spread on solids

Material Factors		**Environmental factors**
Chemical	**Physical**	
Composition of Fuel	Initial temperature	Composition of atmosphere
Presence of retardants	Surface orientation	Pressure of atmosphere
	Direction of propagation	Temperature
	Thickness	Imposed heat flux
	Thermal capacity	Air velocity
	Thermal conductivity	
	Density	
	Geometry	

In summary, flame spread on a solid is often classified as wind-aided or opposed flame spread and is affected to varying degrees by material factors such as thickness and orientation, as well as environmental factors such as airflows and temperatures. Friedman (Friedman, 1977) summarises the factors affecting flame spread over combustible solids, irrespective of air flow, as shown in Table 3.1. He adds atmospheric conditions and pressure to the factors already discussed as these control the availability of oxygen to the combustion process.

3.2 Fire Growth on Wooden Linings in Compartment Fires

The following section intends to explain the current understanding of role of flame spread in the development of a compartment fire, and its effect on tenability. This study focuses on timber linings due to its treatment in the New Zealand fire design, as well as the fact that it is a common combustible lining, thus this chapter focuses on the known effects of timber linings in compartment fires.

A 'compartment fire' refers to a fire which is confined within a room or enclosure. Dimensions are important to fire development, however, most compartment fire research takes place inside compartments of 100 m^2 or smaller, for practical reasons (Drysdale, 1994). Fire growth in a compartment has generally been divided into three stages:

1. The growth or pre-flashover stage in which the fire is average gas temperature is similar to ordinary conditions (Quintiere, 1998), and burning is local to the fire source (Drysdale, 1994).
2. The fully developed or post flashover fire during where all combustible items are involved.
3. The decay period, classed by Drysdale (Drysdale, 1994) as that stage of the fire after the average gas temperature has fallen to 80 per cent of its peak value.

This study is primarily concerned with the contribution of internal linings to the rate of growth of a fire, or stage 1. The rate of growth of a real compartment fire is important as it dictates the amount of time available for occupants to egress, before flashover (which is widely accepted as almost non-survivable) occurs.

It is widely accepted that the rate of flame spread is a significant factor in the fire growth stage of a compartment fire (Thomas, 1981). In the 1960s, as part of a study conducted by the International Building Council (CIB) nine laboratories around the world took part in a single study investigating small scale compartment fires with wood cribs as the fuel bed. 256 separate compartment fires were observed, and four factors were identified as having a first order effect on the time to flashover: the area of the ignition source, the fuel height, the bulk density of the fuel and the compartment lining material (Heselden & Melinek, 1975).

Given the importance of lining materials to fire growth, further studies have sought to evaluate model flame spread on linings in enclosures. Quintiere (1993), Wade and Barnett (1997), and Lattimer (2003) have developed correlations for fire growth in the ISO 9705 room corner test such as using material properties from the cone calorimeter. These methods have generally been shown to be achievable to a reasonable degree of accuracy (see Section 3.3). However, larger scale enclosures have received less attention. Wade and Barnett (1997) showed that using the model for larger scale rooms was less accurate than when it is used for modelling fire development in the ISO 9705 enclosure. All three studies used wooden linings to evaluate their models. Further models for flame spread (specifically using zone models) are described in Section 3.3.

The contribution of wooden linings to flashover in the ISO 9705 enclosures was coupled with the contribution of variable fuel loads in Studhalter's work (2012). Studhalter opted to use wooden linings in his study, citing its popularity as a building material due to its environmental benefits and "cultural importance." Studhalter probabilistically compared times to flashover in a compartment with wooden and non-combustible linings with fuel loads of various sizes and locations using the fire model B-RISK. He observed that compared to a room with non-combustible linings, the median time to flashover occurred a minute earlier if the walls and ceiling were lined with wooden materials, even when uncertainties in the fuel load configuration have been addressed.

Lai et al. (Lai, Tsai, & Lin, 2010) reviewed the times to flashover of 10 small compartment fires (areas up to 99 m^2) in three different studies, including various lining types (concrete, plasterboard, particle board or plywood) and fuel loads (domestic furniture). Flashover occurred generally between 100 s and 178 s. The shortest flashover time (100 s) recorded in an experiment where the walls and ceiling were lined with paper-faced gypsum wallboard. Slightly longer flashover times (106 s to 117 s) were observed for plywood walls and the longest flashover time was in a compartment with concrete walls.

Despite significant research into predicting the performance of compartment fires with wooden linings, little research has taken place into enclosures where the walls are only partially lined with combustible timber linings. While Wade and Barnett (1997) and Lattimer (2003) have both included ceiling only and wall only scenarios in their respective studies, there is little work on compartment fires with partial timber, or even other partial combustible linings. Kambe, Hasemi and Yasui (2015) undertook 12 full-scale fire tests in simulated classrooms using various combinations of wooden and non- combustible wall and ceiling linings, as well as varying openings and eaves, and included some partially lined walls. It was concluded that whether or not the ceiling was lined with wooden linings had the most significant effect on the time to flashover, however no comment was made as to the effect of the partial wall linings.

In summary, fire development in compartments similar in size to the ISO 9075 is well documented, and there is a consensus to the most important factors in this development in which the effect of interior linings is included. There are models available to predict the contribution of timber linings of entire walls and/or ceilings to small compartment fires. However, little research has been undertaken into the effect of partial timber linings in an ISO 9705 compartment on the time to flashover, and to the author's knowledge, there are no existing zone fire models which have been used to model the effect of partial combustible linings on small compartment fires.

3.3 Application of flame spread theory to zone models

3.3.1 Background to Zone Modelling

Zone models are computer models that divide the fire compartments into separate zones, where the conditions (temperature, density etc.) in each zone are assumed to be uniform. Zone models are preferred over other modelling tools, such as field models (which divide a space into numerous cells and calculates variables for each cell at each time point) when simple, rapid calculation is required.

Although other methods are sometimes used, a zone fire model often comprises two zones – a hot upper layer, and a cooler lower layer. The zones are modelled as internally homogeneous, wherein they have a uniform temperature and species concentration throughout the layer. The two zones are linked by the fire, which is generally modelled by specifying, directly or indirectly (e.g. by specifying fuel, burning rates etc.,) a heat release rate. In some models such as CFAST (Lattimer, Hunt, Wright, & Usman, 2003) and the underlying zone model of B-RISK (Wade, et al., 2013), the physics of heat and mass transfer between each layer are based on first principles: mass and energy is conserved within the space, and on this basis, ordinary differential equations are solved at each time point to compute conditions such as temperature of each zone as the fire develops. In other models, such as WPI/Fire Code, the physics are approximated with best-fit equations based on empirical fire tests.

In general, zone models based on first principles do not deal with conservation equations of momentum, so the layers are assumed to be formed instantaneously, i.e. there is often no consideration of a ceiling jet development. This assumption of a generalised layer temperatures have significant implications: in large spaces or spaces with complex geometry, variations in temperature which occur due to delays and heat and smoke travel throughout the space or other reasons across the space will not be represented.

Work has been done to include flame spread models in zone models. Three examples of these are the work by Lattimer et. al. (2003), Gojkovic and Hultquist (1999), and Wade and Barnett (1997). Wade and Barnett's model B-RISK which has been modified for use in this study as described in Chapter 4, is a later version of the zone model BRANZFIRE which described in this section. These studies examine how well the zone models are able to predict the heat release rates in the ISO 9705 room where the room is fully lined with a single lining material.

The following sections outline three studies where zone models have been modified to include capabilities to model the effect of combustible interior linings on fire development

3.3.2 Lattimer, Hunt, Wright and Beyler – Corner Fire Growth in a Room with a Combustible Lining (2002)

This enclosure fire model was developed for the U.S. Navy to provide a means of evaluating newly designed interior linings for their potential contribution to fire development without requiring large scale tests. The model comprises a compartment fire model and a flame spread program (Lattimer B. Y., Hunt, Wright, & Beyler, 2002). The compartment fire model is the model CFAST 3.1.2, an established two-layer zone model developed at National Institute of Standards and Technology (Peacock, Forney, Reneke, Portier, & Jones, 1993). The CFAST model calculates the upper layer gas temperatures based on mass and energy conservation. The flame spread model, as developed by Beyler, et al. (1999) and Lattimer, et al. (1999), then uses the upper layer gas temperatures to calculate the cumulative area of burning linings inside the compartment. The heat release rate of the lining material at each incident heat flux is characterised using the results of cone calorimeter testing.

In order to calculate the contribution of the burning linings to the total heat release rate, the combustible linings are divided into uniform cells. During the fire each cell is either undergoing pre-heating, burning, or has burnt out. Initially the cell is pre-heated, where the temperature rise of each cell is found by calculating the heat transferred from the hot gases and radiation from the predefined source fire to the material at each time step. The preheated cell "ignites" when its surface temperature equals the material ignition temperature. Following ignition, the cell is modelled as burning wherein the heat release rate of a cell is derived from the net heat flux into the material and the heat release rate of the cell material as found from the cone calorimeter tests. Each cell burns out once when the total potential heat release has been exhausted. The heat release rate from all burning cells is added to the heat release rate of the initiating source fire at each time step to model the total heat release rate of the compartment fire (Lattimer B. Y., Hunt, Wright, & Beyler, 2002).

The fire growth model has been validated against a series of ISO 9705 room corner fire tests on eight different composite materials, which comprise polyester and acrylic materials. While it was noted in the test report that the model is capable of predicting the performance of partially lined enclosures, the experiments undertaken for validation used only fully lined enclosures (Lattimer B. Y., Hunt, Wright, & Beyler, 2002).

The model was capable of predicting which lining materials caused the room to reach flashover. Overall, the predicted times to reach flashover were in good agreement with the data. The predicted times to reach flashover were within +/- 135 seconds of the data. In three of the tests, the model predicting flashover to occur later than was observed experimentally, while in two of the tests the modelled flashover occurred before the experimental flashover, while the model accurately predicted no flashover in the remaining three tests. The worst result occurred where the product included a flame retardant, where flashover was predicted 222 seconds before it was observed in the test.

3.3.3 Gojkovic and Hultquist - Incorporating Flame Spread and Fire Growth Algorithms into a Computational Zone Model (1999)

In this thesis, Gojkovic and Hultquist (1999) incorporated a flame-spread model, the so-called Baroudi/Kokkala algorithm, into the WPI/Fire Code. The WPI/Fire Code is a computational zone-type fire model developed at Worcester Polytechnic Institute, Massachusetts. It is different to B-RISK and CFAST in that WPI/FireCode has the option of including heat transfer to the ceiling from a theoretical ceiling jet, based on empirical fire tests, instead of relying solely on the conservation of mass and energy. The Baroudi/Kokkala flame spread algorithm is based on Karlsson's flame spread correlations (Karlsson, 1992) which includes several simplifications, including using an average flame velocity, attempts to better represent flame and pyrolysis heights during the periods when the flame is receding. The flame spread model used in the WPI/Fire Code did not include a model for ceiling spread, thus the ceiling was modelled as an extension of the wall flame spread (Gojkovic & Hultquist, 1999).

In order to benchmark the performance of this model, the model heat release rate output was compared to that of 5 ISO 9705 room tests of gypsum, plastic on gypsum, expanding polystyrene, fibreboard, and paper faced particle board. Agreement between the tested and modelled heat release rates were good for all products, although the model underestimated the heat release rate compared to the experiments in all tests except the expanding polystyrene. Three of the tests achieved flashover or 1 MW of heat release, including where paper on particle board was tested, as well as insulating fibreboard, both, "wood based products" (Gojkovic & Hultquist, 1999). The model successfully predicted the time to flashover for these two products to within 30 s. However, it was noted that layer temperatures were shown to be underestimated by the model, and once the layer temperature reached 300°C, then heat release rate would be drastically overestimated (Gojkovic & Hultquist, 1999).

3.3.4 Wade and Barnett – A Room-Corner Model including Fire Growth on Linings and Enclosure Smoke-filling (1997)

BRANZFIRE (Wade & Barnett, 1997) was developed to combine a zone fire growth model with a modified version of Quintiere's model for flame spread in the ISO 9705 room. The model used in this study, B-RISK (Wade, et al., 2013) is the currently maintained version of this zone fire model, which has been upgraded to include capacity for the probabilistic comparison of fire scenarios where input values take the form of a distribution. The probabilistic capability is not used nor described in this study.

The underlying principles of B-RISK's flame spread and fire growth model, including the modifications for this study are the same in BRANZFIRE, and are explained in Section 4.1. In the publicly available version of B-RISK, and the original BRANZFIRE, the model inputs are for walls or ceilings which are totally lined with a single material. The flame spread and fire growth model have been reported on previously in the literature for small enclosures where the walls and/or ceiling are fully lined with combustible linings. Dowling et al. (1999) compared the times to flashover (FO) of eight ISO 9705 room experiments where various combinations of walls and ceiling were fully lined with combustible materials (untreated plywood, fire retardant plywood and gypsum plasterboard) with simulations using BRANZFIRE. Dowling et al. concluded that for standard plywood (plywood that was not treated with fire retardant coatings or finishes) simulations using BRANZFIRE showed "*very good*" agreement, and the results of his comparison are extracted and shown in Table 3.2. Wade (2013)has also reported on comparisons between model predictions and experiments using data from the EUREFIC research programme and reported "good" agreement between the modelled and experimental results.

Table 3.2: Results of benchmarking study for BRANZFIRE (Wade, 2013).

Material	**Experimental time to FO (s)**	**BRANZFIRE time to FO (s)**	**Δ (s)**
Plywood - walls only	163*	156	7
Plywood - ceiling only	400	380	20
Plywood - walls and ceiling	125	156	31

*average of two tests.

4. Modified B-RISK Flame Spread Capability

4.1 B-RISK – Overview of Flame Spread Model

The fire growth model is an established model within B-RISK. An overview is provided here, full details are provided in the Technical Manual (Wade, et al., 2013).

B-RISK contains a flame spread and fire growth model which accounts for the contribution from burning walls and ceiling to the fire development. It includes algorithms for upward (wind-aided) and lateral flame spread based on Quintiere's (1993) thermal flame spread model for the ISO 9705 room. Wall and ceiling linings are characterised by data from the ISO 5660-1 Cone calorimeter test (or equivalent) and the ASTM E1321 LIFT test. The data needs to include the time to ignition versus heat flux and heat release rate per unit area curves from cone calorimeter experiments as well as lateral flame spread properties from the LIFT apparatus as described in Section 7.3.

Once the user has defined the initial fire source (burner) in terms of the heat release rate, location and geometry, B-RISK calculates the flame height and the heat flux from the burner flame to the wall and ceiling linings. The zone model component also calculates any additional heat flux from the hot gas layer and from other room surfaces and this is added to the burner flame heat flux and used to determine when the wall surface lining ignites.

The ignition time for the wall is determined using the flux-time-product (FTP) method described by Silcock and Shields (1995). Ignition occurs when the accumulated FTP for the lining material reaches the ignition value (for details of how the ignition FTP value is found from the cone calorimeter see 5.4.1) such that:

$$\mathrm{FTP}_{\mathrm{ign}} = \int_0^{t_{ig}} \left(\dot{q}_e'' - \dot{q}_{cr}''\right)^{1/n} dt \qquad [4.1]$$

where $\dot{q}_e''$ is the sum of the incident heat flux from the burner flame, hot layer and other heated room surfaces on the lining and where $\mathrm{FTP}_{\mathrm{ign}}$, n and $\dot{q}_{cr}''$ can be derived from cone calorimeter experiments.

Once ignition of the lining occurs, then the governing equation for upward flame spread is given by:

$$\frac{dy_p}{dt} = \frac{y_f - y_p}{t_{ig}} \qquad [4.2]$$

where $t_{ig} = FTP_{ign} / \left(\dot{q}_{ff}'' - \dot{q}_{cr}''\right)^{1/n}$

The position of the upward pyrolysis front is y_p and y_f is the flame length in the upward direction. The heat flux ahead of the flame $\dot{q}''_{ff}$, is assumed to be 30 kW/m^2. Figure 4.1 and Figure 4.2 show the flame spread for two scenarios, excerpted from (Wade, et al., 2013) and derived from the geometry equations developed by Quintiere (1993).

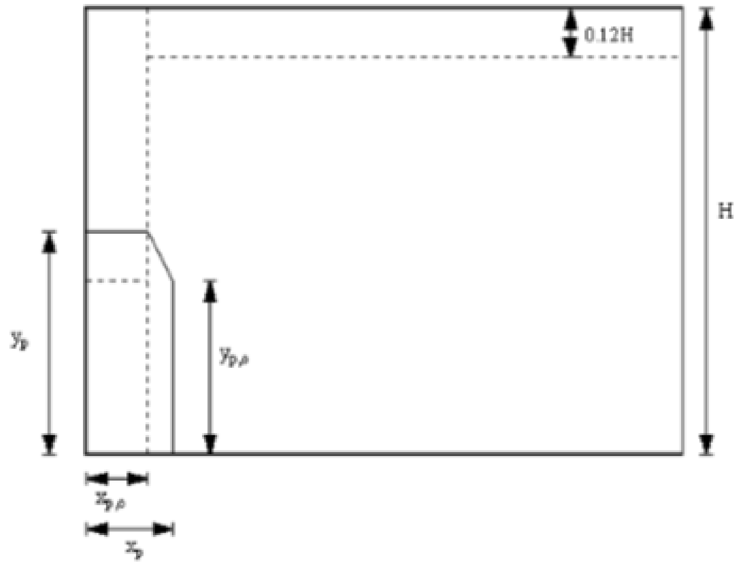

Figure 4.1: Flame spread directions when the ceiling has not ignited

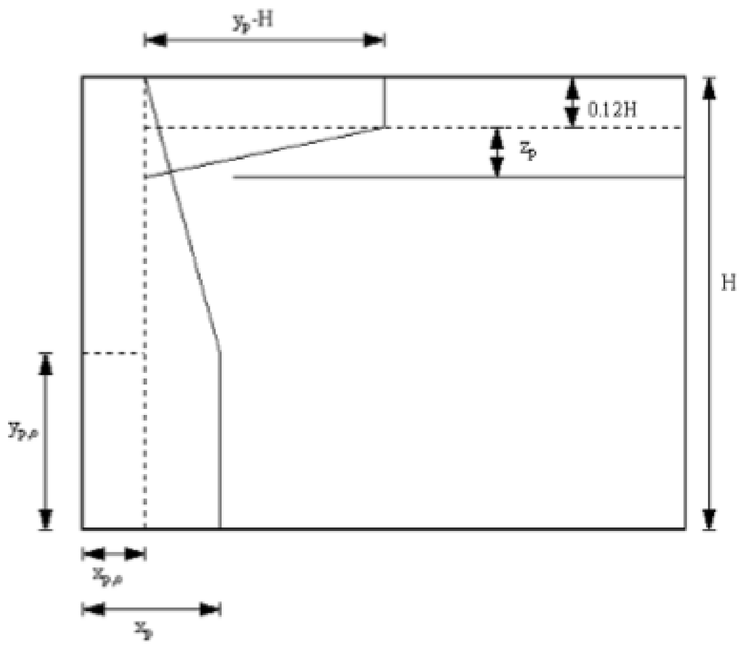

Figure 4.2: Flame spread directions when the ceiling has ignited

The rate of lateral and downward flame spread rate is found from solving the following equation:

$$\frac{dx_p}{dt} = \frac{\varphi}{k\rho c\left(T_{ig} - T_s\right)^2} \quad [4.3]$$

where x_p is the position of the lateral pyrolysis front, φ is the lateral flame spread parameter, $k\rho c$ is the effective thermal inertia, T_{ig} is the material ignition temperature and T_s is the material surface temperature. The surface temperature must be greater than a minimum value $T_{s,min}$ for lateral flame spread to be initiated.

In order to find $T_{s,,}$ the gas layer temperatures are calculated at each time step by the zone model's governing equations based on energy/mass conservation. A one-dimensional finite difference scheme for heat transfer to the room surfaces is used to calculate an average upper wall and lower wall surface temperature. The average upper or lower wall surface temperature from the zone model at each time step is used for T_s depending on the location of the combustible wall compared to the layer height.

The flame spread parameter and $T_{s,min}$ are supplied as input to the model. They are derived from the LIFT apparatus (Anon., 2013) (see Section 7.3 for model inputs for this work).

The position of the upward and lateral pyrolysis front allows the pyrolysis area (A_p) at each time step to be calculated following the area geometry equations given by Quintiere (1993) and represented graphically in Figure 4.1 and Figure 4.2. The total energy released at each time step is the sum of that from the burner, $\dot{Q}_b$, the walls and the ceiling and is given by:

$$\dot{Q}(t) = \dot{Q}_b + \sum\left(\dot{Q}''(t)\Delta A_p(t)\right) \quad [4.4]$$

where $\dot{Q}''$ is the energy released per unit area for each incremental area burning and depends on the elapsed time of burning for each incremental area. This is determined from a set of cone calorimeter heat release rate curves for the material for a range of external heat fluxes. During simulations the curves are interpolated using a cubic spline technique to determine the applicable energy release rate per unit area given the elapsed time from ignition and the calculated imposed heat flux to the wall at that time. If the heat flux imposed to the wall at any point is outside the range of heat fluxes bounded by the cone calorimeter tests, then the data is extrapolated by multiplying the data from the cone calorimeter curve using the nearest heat flux by the ratio of the incident heat flux to the cone calorimeter heat flux.

The burner output and wall/ceiling heat release contribution are combined and modelled as a single plume in the corner of the room. This assumption means that perimeter of the burning area used when calculating entrainment into the plume is underestimated. The model is therefore expected to underestimate the actual entrainment and consequently overestimate the upper gas layer temperature in the room.

4.1.1 Ceiling Ignition

There are two possible ways that the ignition of the ceiling lining is addressed in B-RISK. Firstly, progressive flame spread from the walls can spread onto the ceiling using the flame spread equation [4.2].

Alternatively, the ceiling can ignite independently from the walls due to the fire plume. In this case, for a corner fire, the heat flux to the ceiling is established based on the work of Lattimer (2002) and depends on the burner dimensions, although B-RISK also adds additional heat flux from the gas layer and other surfaces. Ignition is found separately using equation [4.1].

Following ignition, the area of pyrolysis and heat release rate are calculated for each time step as for upward flame spread. However, the area first ignited for a corner fire such as in the ISO 9705 is a quarter circle, which progresses outwards.

Where flame spread from the walls to the ceiling is possible as well as independent ignition of the ceiling, the pyrolysis area is calculated assuming spontaneous ignition of the ceiling, and compared with the pyrolysis area as calculated using flame spread from the walls, and the greater of the two areas is used.

4.2 Modifications to enable modelling of partially lined enclosures

For this study, a developer version of B-RISK included modifications to allow for partial linings. Two approaches to modelling partially lined walls were proposed

Approach 1

To allow for different quantities of wall/ceiling area, the user inputs an x-limit, measured as the horizontal distance from the corner burner which is covered by the combustible lining (this is the maximum limit for x_p in Figure 4.1). The user also specifies a y-limit measured as the vertical distance from the floor covered by the combustible lining (this is the maximum limit for y_p in Figure 4.1) . These two limits would define a rectangular contiguous area bounding the combustible material on the wall. The limits are assumed to extend equally both sides of the burner. The flame spread model used these limits to restrict the maximum pyrolysis area and therefore limit the heat release from the lining material.

Approach 2

An alternative means of inputting the combustible lining configuration requires that the user specifies a percentage of combustible wall and a percentage of combustible ceiling. This area is the maximum area that can contribute to the burning, with the remaining surfaces modelled as non-combustible. The wall or ceiling areas (of burning) returned by the flame spread subroutine are not permitted to exceed these values. This is a worse case assumption in terms of where that combustible material is actually located in the room.

In the case of a partially covered ceiling, the combustible percentage is always required, and it is assumed that the combustible material is located in a radial configuration originating from the burner location. The ceiling can contribute to burning only after the pyrolysis front on the wall has reached the ceiling or when separate independent ignition criteria for the ceiling is met (dependent on the heat flux to the ceiling from the burner flame).

5. Cone Calorimeter Testing

A series of 15 cone calorimeter experiments were carried out to provide data on the ignition and heat release rate behaviour of the plywood, to inform the B-RISK model. Time to ignition at five different heat fluxes was measured and the heat release rate versus time curves for 7 mm thick plywood surface lining material were recorded.

5.1 Experimental Method

5.1.1 Test Product

The test product was 7 mm thick untreated D-grade plywood panels comprising 3-ply pine (pinus radiata) with an average density of 521 kg/m^3. D-grade refers to poor grade timber, which is generally not used as exposed surfaces as it is unsanded, and includes some knots which are not filled. The plywood was untreated.

5.1.2 Test Procedure

The experiments were carried out to ISO 5660-1 (Anon., 2002), in the horizontal orientation with three replicate tests carried out at each heat flux of 20 kW/m^2, 30 kW/m^2, 40 kW/m^2, 50 kW/m^2 and 60 kW/m^2, with ignition piloted by a spark plug. Tests were carried out in a draught free environment over a single day at 30-80% RH and ambient temperature between 16°C to 22°C. The method is described in ISO 5660-1, however, tests were generally stopped earlier than the 30 min required by the standard as the most important information for the B-RISK analysis was the time to ignition, and peak heat release rates, and the heat release rate curves while flaming occurred and it was necessary to complete all the tests in a limited timeframe.

Figure 5.1 shows the test set up. Each sample measured 100 mm by 100 mm, and bottom and sides of the sample was encased in aluminium foil. A 15 mm thick calcium silicate board backing was included to closely represent the surface lining substrate as installed in the full-scale room experiments. The sample was located so that the top face of the sample was situated 25 mm below the cone heating element. The source of the piloted ignition (the spark plug) is situated approximately 13 mm above the centre of the specimen. A 60 s base line was run before each test to stabilise the element temperature. After 60 s, the specimen shield was closed and the specimen was placed on the specimen holder after a further 45 s. The shield was then opened exposing the specimen to the radiant heat flux and the spark igniter was moved into position.

Once the specimen ignited the time was recorded and the spark igniter was removed after sustained flaming was observed.

Figure 5.1: UC Cone calorimeter showing element, sample in steel retainer and spark igniter

5.2 Measurements

The following measurements were taken in order to calculate the inputs to the B-RISK model:

- **Heat release rate** - The combustion gases were collected in the HRR is calculated using the principle of oxygen consumption calorimetry (Huggett, 1980).

- **Mass Loss Rate -** The mass loss rate was measured as the specimen is positioned on a scale during the test. Measurements are recorded every 1 s.

- **Time to ignition -** The time to ignition was measured by timing (with a stopwatch) the time from test start (t =0, when the specimen shield is removed to exposed the sample to the hot element).

5.3 Calibration

The UC Cone Calorimeter was calibrated as by the procedure described in the University of Canterbury Cone Calorimeter Calibration procedure (Greenslade, 1999). The important aspects of the Cone Calorimeter that require accurate calibrations are the conical heating and gas analysers.

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The heat flux from the conical element is calibrated using a heat flux gauge. Each gauge has a specific calibration curve that converts a voltage to a corresponding heat flux. Table 5.1 shows the element temperatures calculated for each required heat flux for this study.

Table 5.1: Cone calorimeter element temperatures for each required heat flux

Heat Flux	Temperature (°C)
20	507
30	602
40	677
50	737
60	793

The gas analysers are calibrated using a 5 kW methane burner. Since the amount of oxygen consumed during complete combustion per kilogram of methane is known, the required flow rate of methane to produce 5 kW is also known. The results of the heat release rate analysis during calibration are verified so they are consistent with these known values and the *C* value, or the mass flow constant which is unique to each calorimeter, is found. This value was required to be within 5 % of the value at previous calibration, or re-calibration was required.

5.3.1 Instrumentation measurement time lags

The calculated HRR is a function of time dependent measured variables. As the sample pyrolyses, ignites, and burns, the combustion gases must travel up the hood, and to the gas analysers. There are therefore time delays that exist between each property being produced and its value being measured, since time elapses between the moment that the specimen observably ignites and burns, and the time that the combustion gases emitted by that event are measured and recorded. There are therefore two delays: transport lag, or the physical time taken for the specimen to travel from the sample to the analyser, and the response time lag, or the period of time needed by the analysers to analyse and record the measurement.

The lag times that occur in the cone calorimeter testing are summarised as follows: the mass scale measures the instantaneous mass of the specimen at each point in time during the experiment (effectively no lag between mass and the actual combustion). There is then a delay (transport lag) before the gas specimen emitted at the point of combustion/mass measurement arrives at the gas analyser via the ducting and sample lines. There is then a further delay (the response lag) as the analyser chemically analyses the sample and derives the proportions of each gas. Therefore, the oxygen calorimetry calculation must incorporate these lag time when comparing gas concentrations to derive the accurate heat release rate at each time interval. The values of lag times input into the heat release rate calculation were based on the lag times recommended in Enright's work (1999), however it was observed that these meant that the observed and record ignition times were not consistent. Thus, the lag times were adjusted so that combustion was observed to begin shortly after ignition.

5.4 Results

5.4.1 Heat release rate curves

The heat release rate characteristics including the peak heat release rate and ignition times are summarised in Table 5.2.

Table 5.2: Cone calorimeter test results for 7 mm plywood

Test	Heat Flux (kW/m^2)	Ignition Time (s)	Peak HRR (kW/m^2)
1	20	366	109
2	20	197	110
3	20	301	144
4	30	66	128
5	30	84	121
6	30	79	121
7	40	33	173.4
8	40	50	165
9	40	30	158.2
10	50	18	253
11	50	22	186.9
12	50	22	203
13	60	14	220.9
14	60	10	267
15	60	10	266

Table 5.3: Standard deviation for ignition times

Heat flux (kW/m^2)	Mean ignition time (s)	Standard deviation of ignition times (s)
20	288	70
30	76	8
40	38	9
50	21	2
60	11	2

The time to ignition results are intuitively predictable: ignition times increase as incident heat flux increases. Table 5.3 shows that in general at lower heat fluxes, the ignition times were higher, but were also less consistent across the repeat tests. At an irradiance of 20 kW/m^2, the mean ignition time was 288 s with a standard deviation of 70 s, while at an irradiance of 60 kW/m^2, the mean ignition time was 11 s with a standard deviation of 2 s.

The heat release rate graphs are shown in Figure 5.3 to Figure 5.7 for each heat flux. In general, these follow the characteristic heat release rate pattern observed in earlier cone calorimeter studies of wood samples (Janssens, 1991). That is, an initial peak shortly after ignition, followed by a decrease in heat release rate at the wood surface chars, shielding the unburnt wood from the pyrolysis front. Once the heat is conducted through the sample, it reaches the unexposed side of the sample which is not charred, and which is insulated from the sample underlay. The rear side surface readily pyrolyses and burns rapidly, forming the second peak. Janssens (1991) notes that the second peak in wood tested under the cone calorimeter is often less pronounced as some heat is inevitably lost to the insulating backing behind the sample, however in the tests shown below; the second peak usually exceeds the first. This is not unheard of, Parker (1986) and Tsandiaris (2003) in separate studies tested particle board and plywood respectively at heat fluxes from 20 – 50 kW/m^2 and also found that the second peak in heat release rate generally exceeded the first peak. In the tests in this study, as shown in Figure 5.2, the thin plywood sample used in this test tended to warp and buckle after the first peak, exposing more of the unburnt underside of the timber to a ready supply of oxygen which, coupled with the pre-heating of the unburnt sample prior to the second peak, may have aided in forming a higher than expected second peak in heat release rate.

Figure 5.2: Sample 11 at 240 s showing cracking, shrinkage and warping. Second peak had occurred at 198 s.

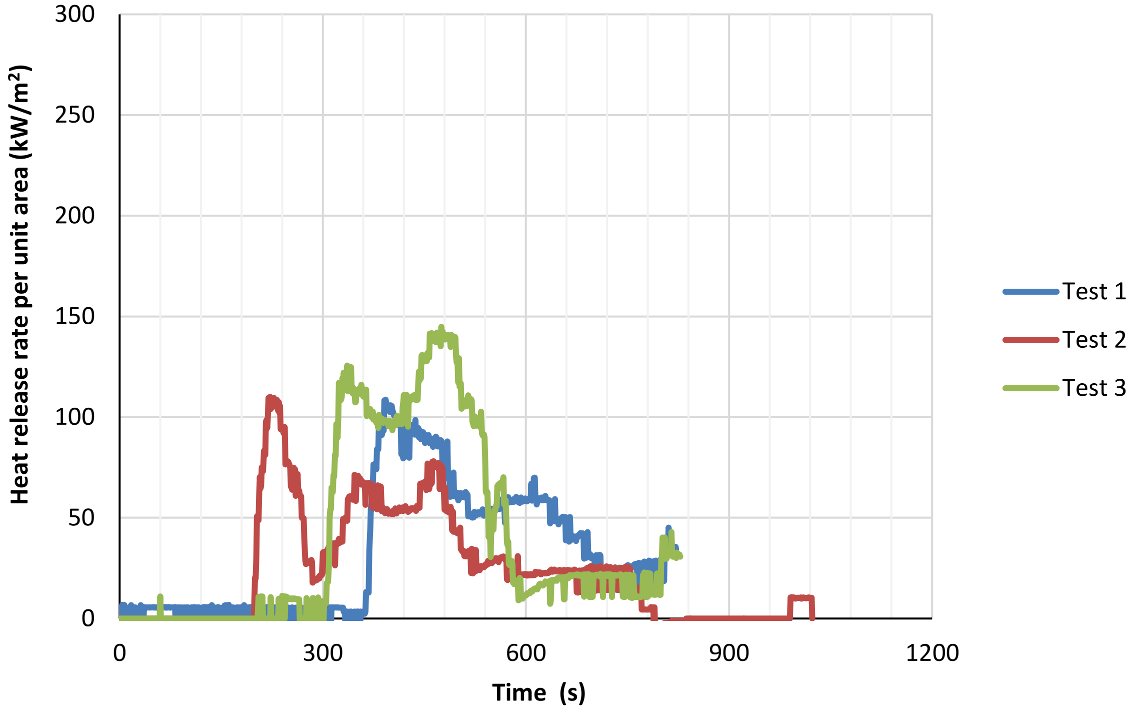


Figure 5.3: Heat release rate curves for cone tests at 20 kW/m^2 incident heat flux

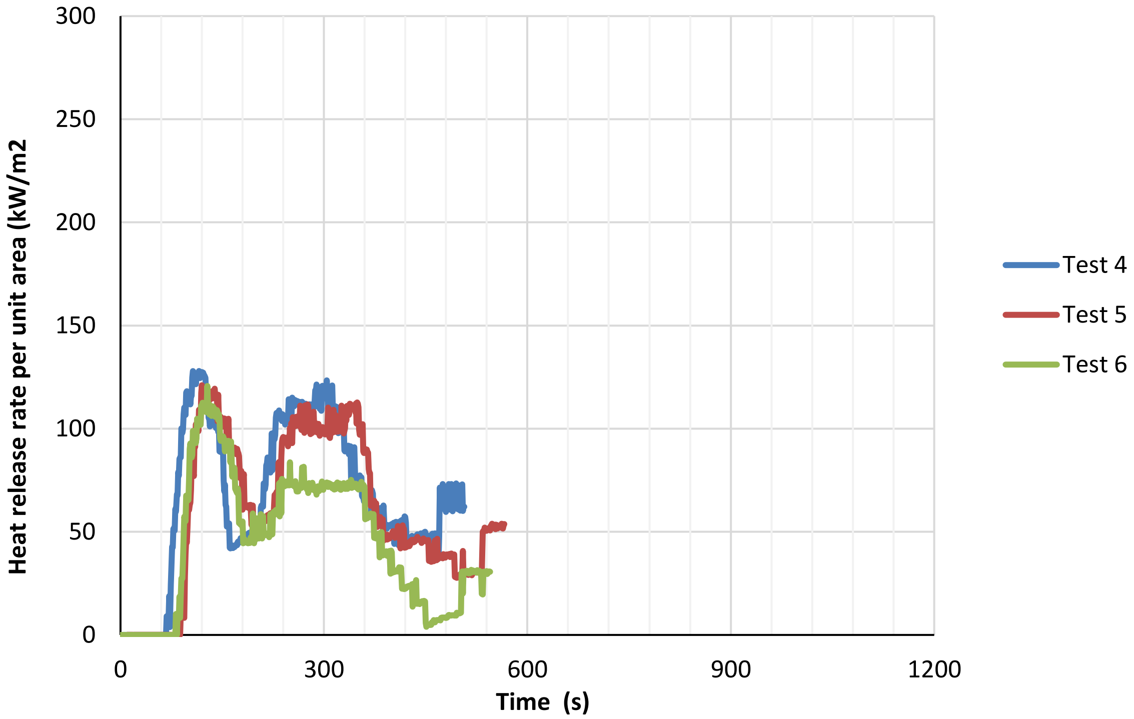


Figure 5.4: Heat release rate curves for cone tests at 30 kW/m^2 incident heat flux

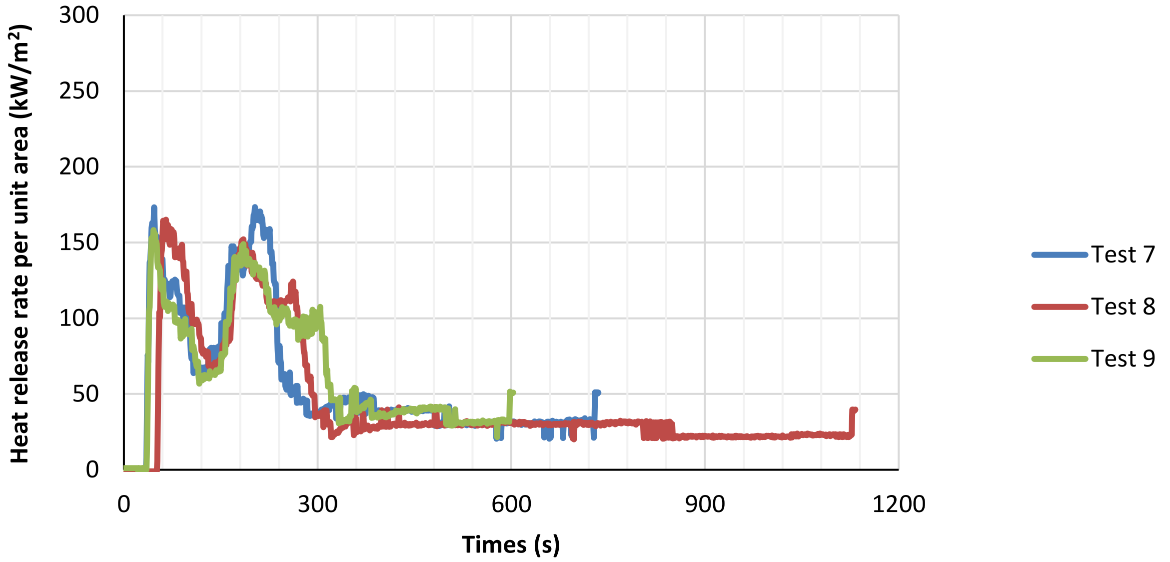


Figure 5.5: Heat release rate curves for cone tests at 40 kW/m^2 incident heat flux

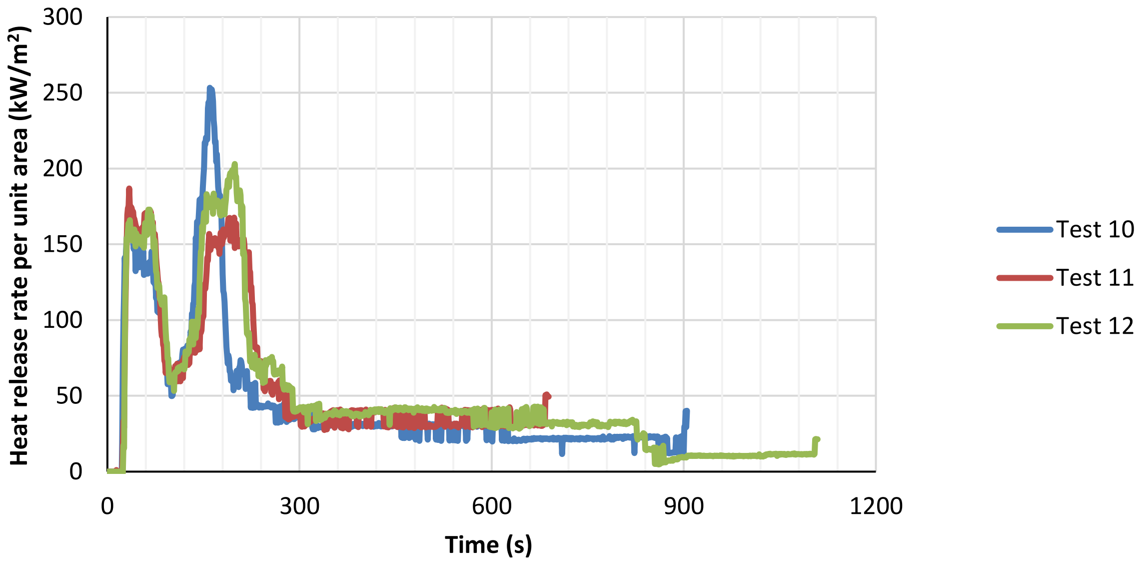


Figure 5.6: Heat release rate curves for cone tests at 50 kW/m^2 incident heat flux

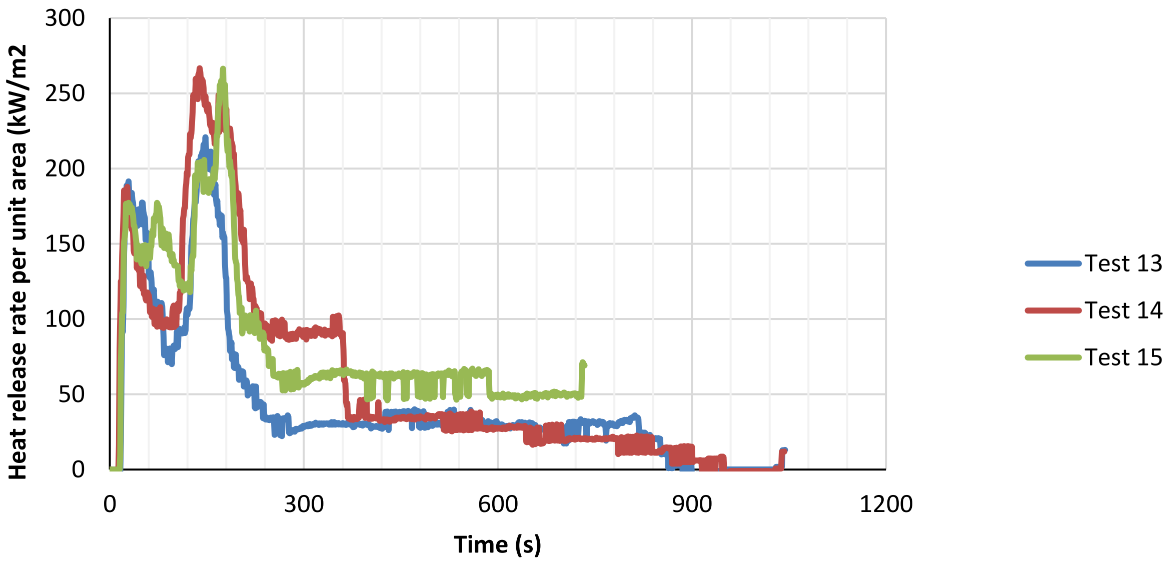


Figure 5.7: Heat release rate curves for cone tests at 60 kW/m^2 incident heat flux

5.4.2 Effective heat of combustion

Effective heat of combustion was calculated by dividing the total heat released during each test (in this case, the sum of each heat release at each 1 s time interval) to the overall mass loss. The average effective heat of combustion across all 15 tests was 13.31 MJ/kg (SD = 2.54). The variation (SD =2.54) in the effective heat of combustion in each tests is likely to attributed to variation in the timber used (knots and density variation) as this is a natural product with inherent discrepancies in its fibre make-up. Furthermore, it was observed that the plywood samples contained varying proportions of adhesive which have different combustion properties to timber and in some tests, appeared to melt and drip away from the apparatus without burning completely, thus reducing the mass without contributing to combustion.

Table 5.4: Effective heat of combustions for each test

Test	Heat Flux (kW/m^2)	Effective Heat of Combustion
1	20	9.75
2	20	10.08
3	20	10.65
4	30	12.47
5	30	14.35
6	30	9.23
7	40	13.34
8	40	12.82
9	40	12.7
10	50	12.76
11	50	13.6
12	50	16.28
13	60	13.54
14	60	17.48
15	60	17.93
	Mean	**13.31**
	Std. Dev.	**2.54**

5.4.3 Plywood density

Immediately prior to testing, each 0.1 m x 0.1 m by .007 m thick sample was weighed and its mass was recorded (Table 5.5). Even when possible variation in how precisely the samples were cut to size is considered, there is noticeable variation in the mass and therefore density of each sample (SD = 16.6), with a mean density of 521 kg/m^3. Given that this is low grade plywood, it is likely that the knots in the wood, visible in Figure 5.8 as well as variation in the adhesive application thickness within the layers contribute to the variation in density across each plywood board.

Table 5.5: Mass measurements of plywood samples.

Sample	Mass (g)	Mass (kg)	Density(kg/m^3)
1	38.1647	0.038165	545.2
2	34.5275	0.034528	493.3
3	37.1709	0.037171	531.0
4	36.839	0.036839	526.3
5	37.1033	0.037103	530.0
6	34.7505	0.034751	496.4
7	36.3478	0.036348	519.3
8	37.4869	0.037487	535.5
9	38.1681	0.038168	545.3
10	34.7923	0.034792	497.0
11	36.012	0.036012	514.5
12	36.3506	0.036351	519.3
13	36.3029	0.036303	518.6
14	35.3117	0.035312	504.5
15	37.6478	0.037648	537.8
		Mean	**520.9**
		Std.Dev.	**16.6**

Figure 5.8: Sample of the 7 mm plywood product (note: taken from full scale Experiment 1 in this study) showing presence of knots and defects. Dark staining is melted adhesive.

5.4.1 Ignition criteria

5.4.1.1 Critical Flux-Time-Product (FTP) for Ignition

In order to establish whether a lining in the flame spread model ignites, the required flux-time product for ignition of that product is compared to the accumulated flux time product at each time step as shown in Equation [4.1]. The flux-time product is also used to derive the rate of upward spread (see Equation [4.2]).

To estimate the critical flux-time product and thermal inertia of the plywood, all 15 ignition times were included in the input file used for the B-RISK modelling and are processed in B-RISK .

The ignition times were correlated in B-RISK by plotting $(1/t_{ig})^n$ versus the external heat flux as shown in Figure 5.9. The value of *n* in the range 0.5 to 1.0 that results in the highest correlation coefficient (r^2) was determined. The value of *n* was found to be 0.56 with r^2=0.96. The critical heat flux represented by the horizontal axis intercept was found to be 13.1 kW/m^2.

The ignition temperature, T_{ig}, for the plywood was determined by solving equation [5.1] by iteration and taking the surface emissivity ε as 0.9, the convective heat transfer coefficient h_c as 0.0135 kW/m^{2}K as recommended by Janssens (1992), ambient temperature T_∞ as 293 K and critical heat flux as 13.1 kW/m^2.

$$\epsilon \dot{q}_{cr} = h_c\left(T_{ig} - T_\infty\right) + \epsilon\sigma\left(T_{ig}^4 - T_\infty^4\right) \qquad [5.1]$$

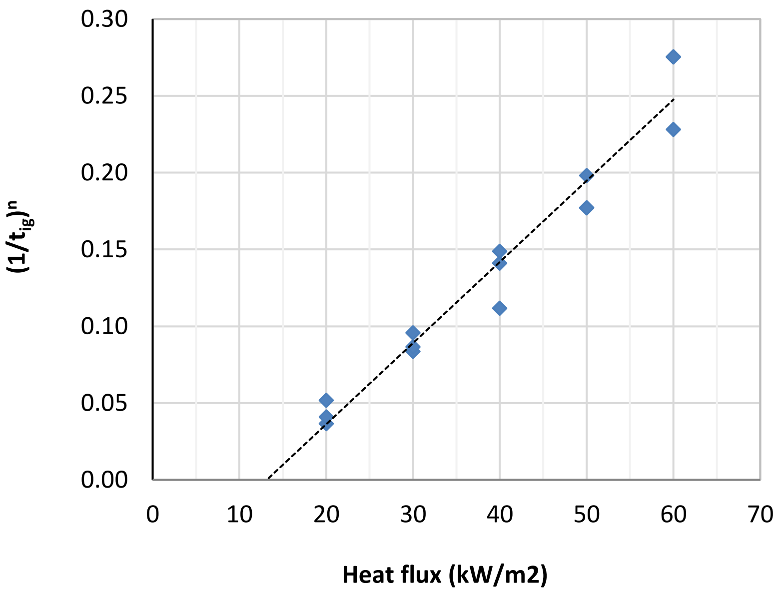


Figure 5.9: Correlation of ignition times to find critical heat flux, and best fit *n*.

The ignition temperature for the plywood was calculated as 622.5 K. The FTP value for ignition was determined from the small-scale ignition data and equation [4.1] to be 11642 [s.(kW/m^2)$^{(1/0.56)}$].

6. Partially Lined ISO 9705 Experiments

In order to investigate the contribution of partial linings to fire development in a compartment, seven full-scale room experiments have been conducted in the conditions required by ISO 9705 except the walls were partially lined in various configurations with plywood panels

In keeping with the broad objectives described in Section 1.3, the objectives of the full-scale room experiments were:

1. Investigate and develop a method of comparison of heat release rates for various partially lined enclosures.
2. Provide data on heat release rate, layer temperature and flame spread rates, for comparison with computer modelling using B-RISK.

The tests used the same 7 mm thick pine plywood as used in the cone calorimeter experiments

6.1 Test Enclosure

The test enclosure was a room constructed from lightweight concrete panels. A light-gauge steel frame was constructed on the inside and one layer of 7 mm thick plywood was screw fixed to the steel frame. One layer of non-combustible 15 mm thick calcium silicate board (with a density of 975 kg/m^3) was then screw fixed on the room side covering the plywood substrate.

The internal dimensions of the enclosure with the calcium silicate board in place but before installation of the test product was 3.43 m long × 2.11 m wide × 2.21 m high. An opening (0.81 m wide × 1.955 m high) was centrally located in the short wall opposite the burner corner. A propane burner measuring 170 mm by 170 mm with the top surface 300 mm above floor level was located in the corner opposite the opening.

This construction was used for all seven tests with the test product installed in place on the surface by screw fixings through the calcium silicate board and into the plywood substrate behind. To facilitate the observation of flame spread during the test, the plywood was marked with a grid denoting 200 mm by 200 mm squares (Figure 6.1).

Figure 6.1: Fully lined ISO 9705 room

6.2 Measurements

6.2.1 Heat release rate

During the experiments combustion gases were collected by the hood located outside the opening and the rate of heat release (HRR) measured using oxygen depletion calorimetry as per ISO 9705. The heat release rate from the compartment is calculated every 3 seconds.

The total rate of heat release shown in the Section 0 includes the burner rate of heat release. Initially the burner rate of heat release (derived from the gas flow rate) appears to exceed the total rate of heat release measured by the calorimeter. This is because the combustion gases must first form a smoke layer before flowing through the opening into the collection hood and exhaust duct to be analysed. Therefore the total rate of heat release is underestimated during the first 1-2 min of each experiment.

Water from an open sprinkler head in the room was used to extinguish those experiments which reached flashover.

6.2.2 Gas Temperature

Temperature was measured using K-type thermocouples located in a steel tree in the corner beside the door, opposite the burner. Thermocouples were located 300 mm from each wall, and at heights of 2100 mm, 1720 mm, 1580 mm, 1420 mm, 1280 mm, 970mm and 670 mm above the enclosure floor level. Temperature readings were recorded every 3 seconds.

The layer interface temperature, used to approximate the layer interface height between the upper and lower layers, was calculated using linear interpolation of the seven point measurements calculated using the method described in NFPA 92 (2015) for the upper layer interface temperature, T_{int}, based on the work by Cooper et al. (Cooper, Harkleroad, Quintiere, & Rinkinen, 1982):

$$T_{int} = C_n(T_{max} - T_b) + T_b \qquad [6.1]$$

where:

$$T_{max} = maximum\ thermocouple\ temperature$$
$$T_b = minimum\ thermocouple\ temperature$$
$$C_n = interpolation\ constant, 0.8$$

The height of the upper layer above floor level is found by interpolation of the temperature values, and the height above floor level at which T_{int} is the height of the smoke layer interface.

NFPA 92B describes a C_n value 0f 0.8-0.9 for the smoke interface temperature, whereas C_n= 0.1-0.2 is the temperature at the first indication of smoke (NFPA 92: Standard on smoke control systems, 2015). A value of 0.8 is used as this value which matched the observed layer height most reasonably and gave the layer heights closest to the ceiling at the start of the test, when the layer is closest to the ceiling. A significant limitation to calculating the layer height in the enclosure was that the highest thermocouple was located 2100 mm above the floor of the enclosure, or 100 mm below the ceiling, and the lowest thermocouple at 670 mm above floor. This means that at time = 0 s, it was assumed that the layer height was at 2100 mm already, as data could not reasonably be extrapolated above this point. It was also not possible to accurately calculate layer heights below 670 mm. However, the purpose of estimating layer height was to compare the experimental layer height with the modelled layer height. Since the layer was observed to be mostly located between 670 mm and 2100 mm, this comparison was still valuable to gain an indication of model performance compared to the experiments.

The upper layer temperature was also calculated based on NFPA 92 (NFPA 92: Standard on smoke control systems, 2015). The temperature within the upper layer was assumed to increase linearly above the layer interface, so the average upper layer temperature was found as the mean of the interface temperature and the upper most thermocouple located at 2100 mm.

6.2.3 Flame Spread

The experiments were recorded using video and still photography. A webcam was located in the doorway, as well as an additional video camera angled from outside the door.

Flame spread rates were measured by identifying the location of the flame spread front at 60 s intervals using the grid and dividing this progress over the elapsed time. Where flame spread rates were rapid, and the flame spread was not obscured by smoke or debris, flame spread rates over 30 s intervals were also measured. It is important to note that early flame spread was generally obscured by the flames from the gas burner, so rates (during the first 40–80 s) are higher than would ordinarily be expected for the early stages of flame development on timber.

Horizontal flame spread, as discussed in this report, is the flame spread parallel to the floor and is measured at the mid-height of the wall lining on the short wall adjacent to the burner. Downward flame spread is measured at the centre of the short wall (and in some cases, eventually obscures horizontal spread). The ceiling (jet) flame spread refers to the early horizontal flame spread on the upper 400 mm of the walls and is measured until the upper wall was completely involved or flaming had stopped.

6.3 Configurations

Seven configurations of plywood linings and exposed calcium silicate were tested in the ISO 9705 enclosure, summarised in Table 6.1. The partially lined configurations are illustrated in Figure 6.3 to Figure 6.8. A fully lined room to ISO 9705 (Experiment 1) was included to provide a reference scenario (Figure 6.2), against which the performance of the partially lined enclosure could be compared. It was also included to assess whether the 7 mm plywood achieved Group 3 according to the New Zealand Building Code as it was thinner than the minimum acceptable thickness (9 mm) permitted by the New Zealand design guidance to achieve a generic Group 3 rating (New Zealand Government, 2014).

Table 6.1 Lining configurations used in the experiments.

Expt	Location of timber wall linings	Ceiling lined?	Total timber area (m^2)	Timber above 1.2 m (m^2)
1	ISO 9705 (three walls)	Yes	31.7	20.16
2	None	Yes	8.64	8.64
3	Lower half of walls to 3.6 m from burner corner	No	8.64	0
4	Upper half of walls to 3.6 m from burner corner	No	8.64	8.64
5	Full height walls to 2.4 m from burner corner	No	11.5	5.76
6	Full height walls to 3.6 m from burner corner	No	17.3	8.64
7	Full height walls lined 1.2 m h from burner corner	Yes	14.4	14.4

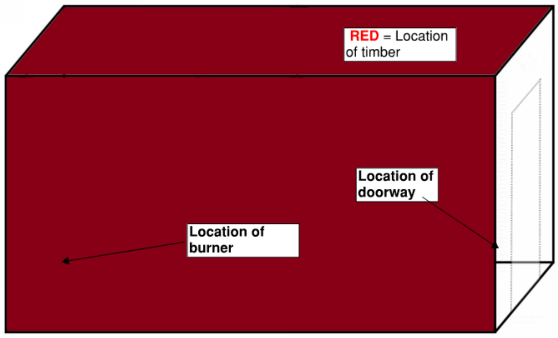


Figure 6.2: Expt. 1 - ISO 9705 lining layout with ceiling, rear wall and two adjacent walls lined.

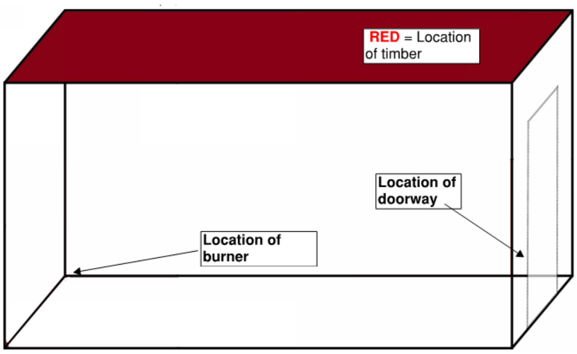


Figure 6.3: Expt. 2 – Ceiling lined only

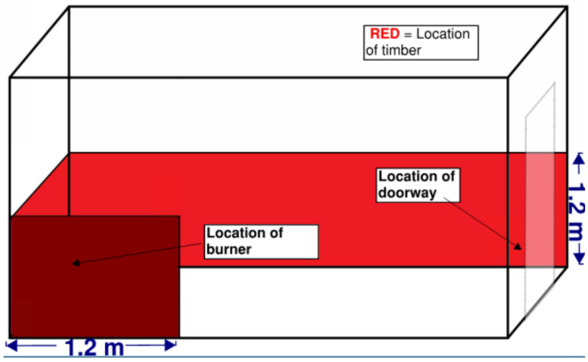


Figure 6.4: Expt. 3 – Lower half of walls lined to 1.2 m above floor to 3.6 m horizontally from burner corner.

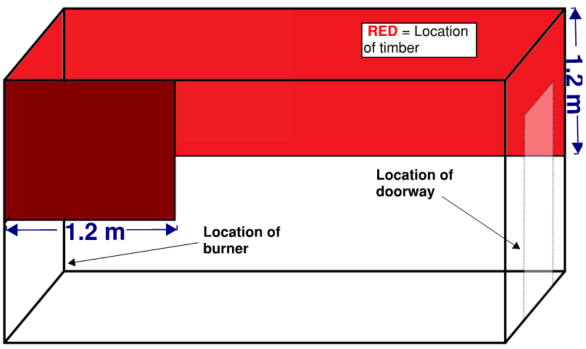


Figure 6.5: Expt. 4 - Upper half of walls lined from 1.2 m above floor to 3.6 m horizontally from burner corner.

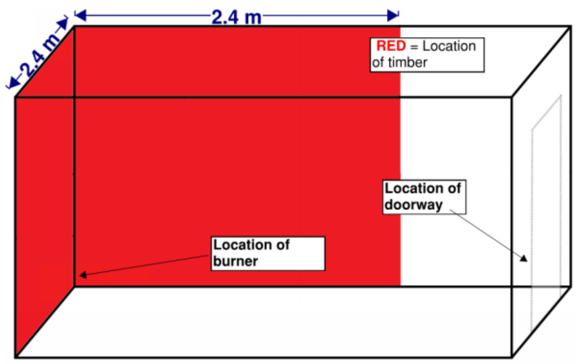


Figure 6.6: Expt. 5 –Walls lined to full height to 2.4 m horizontally from burner corner

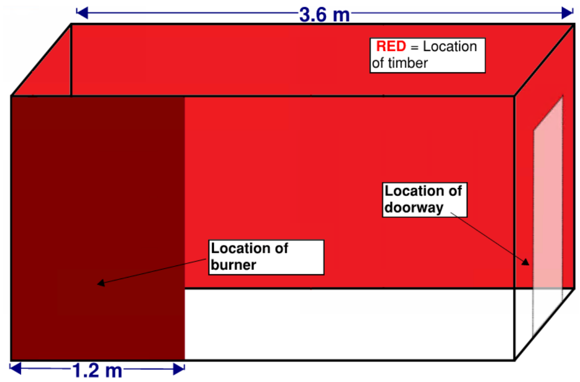


Figure 6.7: Expt. 6 –Walls lined to full height to 3.6 m horizontally from burner corner

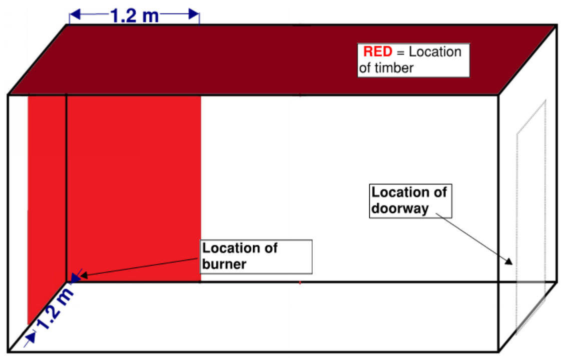


Figure 6.8: Expt. 7 - Ceiling lined and walls lined to full height to 1.2 m horizontally from burner corner

Configurations used in Experiments 2 (Figure 6.3), 3 (Figure 6.4), 4 (Figure 6.5) and 7 (Figure 6.8) in particular were specifically included to provide insight into the contribution of ceiling linings and/or upper wall linings to fire development to reflect the philosophy behind the differences in permissible wall and ceiling linings. The review of building code requirements as described in Section 2.2 showed that in several jurisdictions, such as New Zealand, Australia and Canada, timber located at high levels in a space (i.e. on the upper walls or ceiling) was treated more severely than timber on the lower half of the buildings. Therefore, these configurations were intended to replicate these concessions to validate the need for these types of concessions in design guidance.

Experiment 7 included partial lining of the two walls closest to the burner to examine the effect of adding a 'path' for flame spread to reach the ceiling. In a realistic fire scenario, this path could take the form of a combustible wall lining or decoration, or alternatively another furnishing such as a shelf or joinery.

The configurations were developed in order to be readily compared with the flame spread, rate of heat release and time to flashover calculated using a modified version of B-RISK (Wade, et al., 2013), thus they were generally symmetrical either side of the burner, and continuous from floor level (for detail model geometry requirements see Section 7.1). Configurations 5 and 6 were included to examine the accuracy of the simulated scenarios, by testing whether the additional 1.2 m of timber in Configuration 6 would have a significant impact on the experimental and modelled results between the two configuration.

Given the limited number of tests, a test where a single wall was lined was not included despite timber or other combustible- lined "feature walls" being a common design feature. This was because a corner scenario such as Configuration 5 and 6 positions more fuel close to the burner than a single wall, and are likely to encourage a more severe fire than a single wall. Conclusions regarding the severity of fires derived from testing Configurations 5 and 6 could therefore conservatively also be applied to a single wall scenario.

6.4 Experimental Results and Discussion

6.4.1 Rate of heat release

Table 6.2 summarises the time to flashover (FO) for each scenario, or where no flashover occurred, the peak rate of heat release including the burner rate of heat release is given, along with the time taken to reach this value. Table 6.2 also summarises the percentage of the total room wall and ceiling area that is lined with timber (where a room lined in accordance with ISO 9705 is 85% lined, since the short wall at the opening end of the room is unlined). The percentage of this area that is eventually charred and the percentage of the timber lining charred is also shown. $FIGRA_{RC}$ (FIre GRowth Rate - Room Corner) is calculated as described by Sundström (Sundström, 2007) (see Section 2.4.1.1 for calculation method).

The heat release rate of the burner is derived from the mass flow rate of the fuel gas and its heat of combustion, and is not derived from oxygen calorimetry. The total heat release rate of the graph is derived from oxygen calorimetry and includes the contribution from the burner.

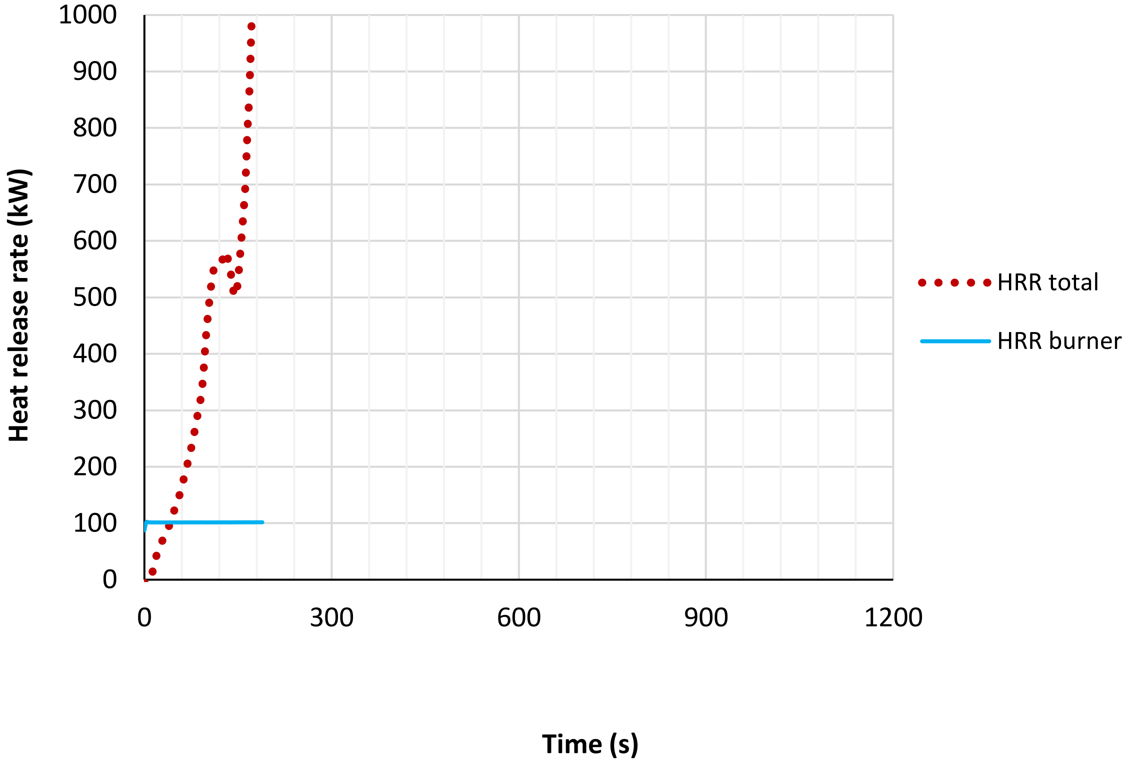
Table 6.2: Summary of experimental results of seven large scale tests.

Expt	Time to FO (s)	Peak HRR (kW)	Time to peak HRR (s)	% room lined	% lining charred	% room charred	$FIGRA_{RC}$ (kW/s)
1	174	-	-	85	66	58	5.17
2	No FO	809	723	23	100	23	0.70
3	No FO	600	1200	23	56	13	0.25
4	No FO	941	486	23	100	23	1.73
5	630	-	-	30	100	30	1.11
6	414	-	-	46	90	42	2.17
7	366	-	-	38	99	38	2.46

6.4.2 Experiment 1 - Fully lined ISO 9705 Test

The heat release rate (HRR) for the fully lined room reached 1 MW in just under 3 min (Figure 6.9 (a)), which equates to NZBC Group 3. It was also observed that after the test, approximately 66% of the lining showed charring including the entire ceiling, and only 54% of the wall area as shown in Figure 6.9 (b).

a,



b,

Figure 6.9: Experiment 1, (a) rate of heat release, (b) post-experiment charring pattern.

6.4.3 Experiment 2 - Ceiling only

In Experiment 2 it was observed that there was only sporadic direct contact between the burner flames and the plywood lining on the ceiling at 100 kW. The rate of heat release did not reach 1 MW (Figure 6.10(a)) and the fire development was slower than when the equivalent area of timber (8.6 m^2) was located on the upper walls (as in Experiment 4). The peak flame spread rate of 8.3 mm/s during the first 10 min (Figure 6.10(b)) was also less than the peak flame spread rate observed in the ceiling region for the case with plywood at high level on the wall (e.g. 10 mm/s for Experiment 4).

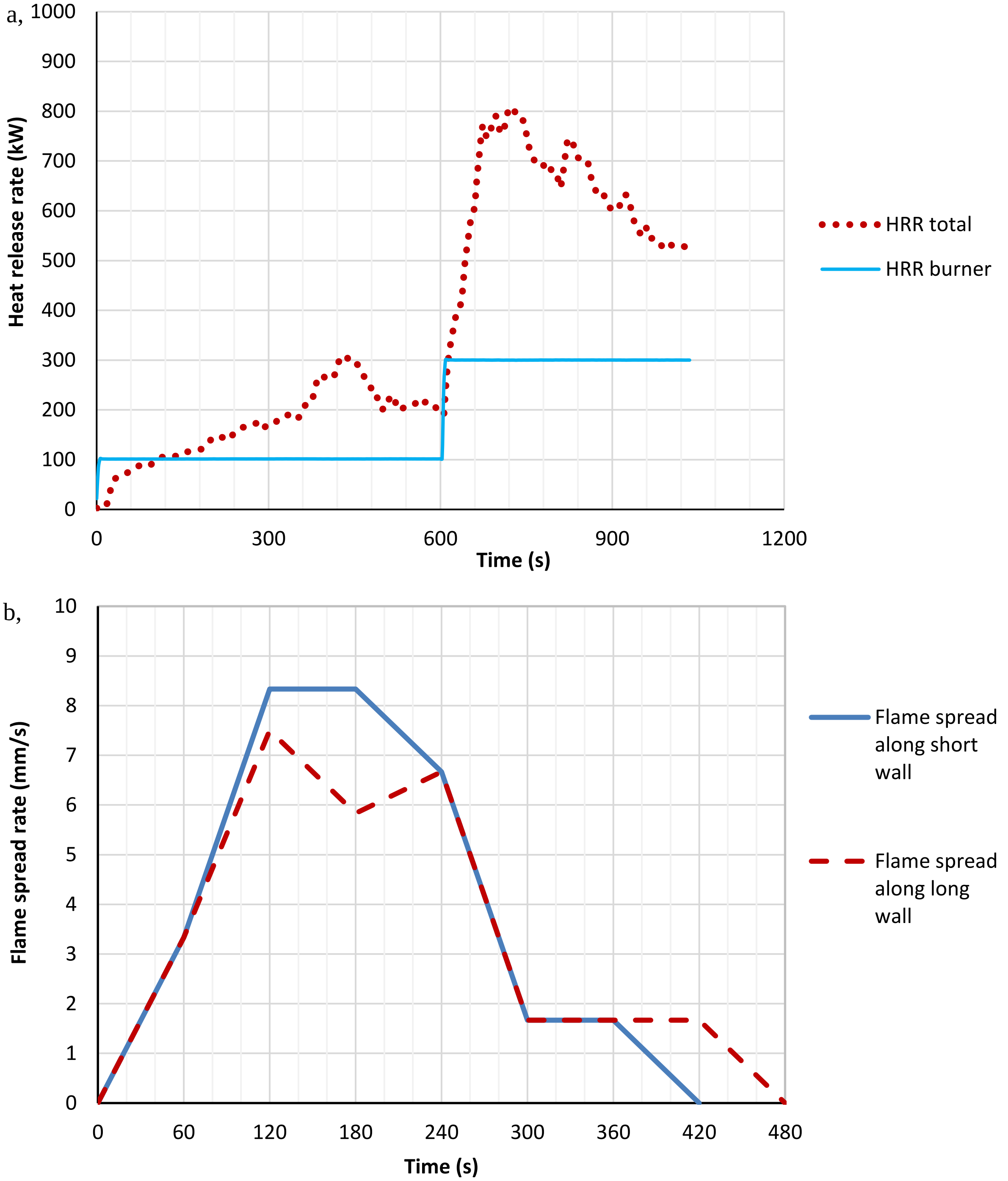


Figure 6.10: Experiment 2, (a) rate of heat release, (b) flame spread rate.

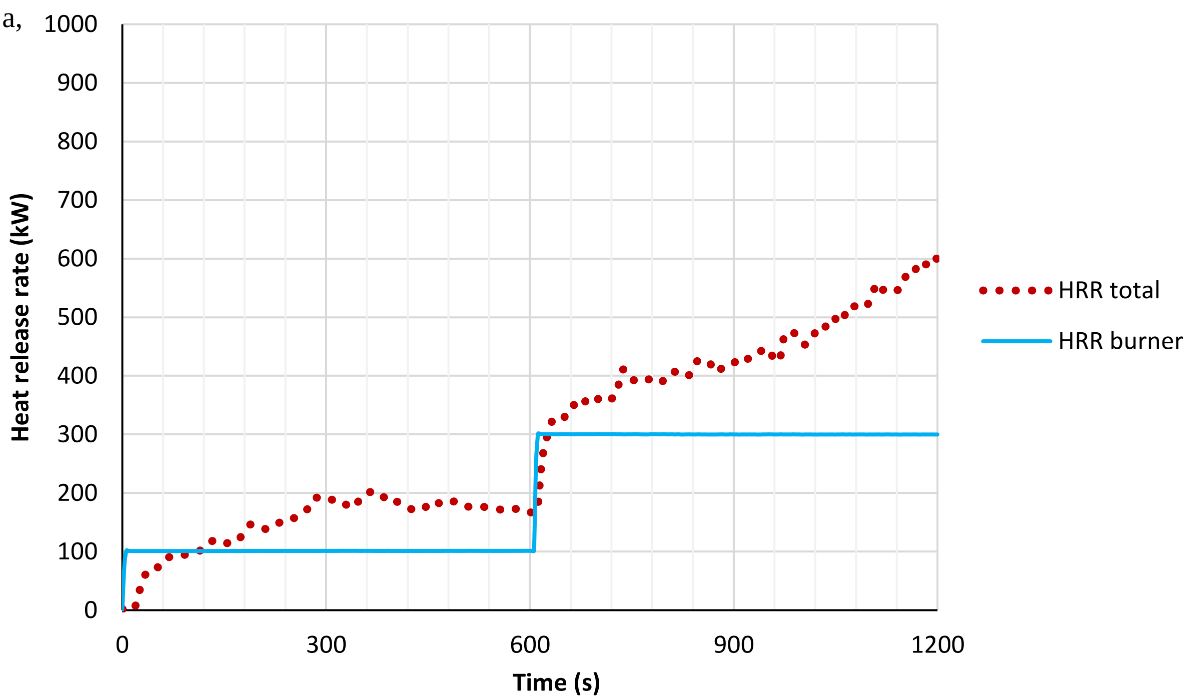
After 4 min flames had spread across nearly 50% of the ceiling. Once the plywood that had ignited had formed a char layer the flame front receded so that only the area directly above the burner was showing flames. At 8 min, this area was completely burnt out to expose the calcium silicate substrate, and there was only intermittent flaming for a 200 mm wide band 1.2 m from the burner corner. No further flame spread measurements were taken as there was no flame on any of the remaining plywood. However, once the burner rate of heat release was increased to 300 kW at 10 min, the ceiling was completely involved by 11 min.

After 15 min the plywood ceiling was fully burnt away to a distance of 2.4 m from the burner, and the rest of the ceiling was charred. There were no visible flames on the remaining 1.2 m of plywood at this point. The experiment was then stopped as flame spread had ceased and no further information regarding fire growth was expected to be found if the experiment were prolonged.

6.4.4 Experiment 3 - Lower Walls

During the first 6 min of Experiment 3, only the plywood that was immediately in contact with the burner flames was consumed. The horizontal flame spread beyond this area was slow (maximum horizontal flame spread rate after intial flaming of 0.5 mm/s, Figure 6.11(b)). The rate of heat release started to decrease at 6 min (Figure 6.11 (a)) until the burner was increased to 300 kW by which point the total horizontal spread was less than 300 mm horizontally from the burner. After 20 min, the maxium rate of heat release of 600 kW was reached and the flames had spread 1200 mm horizontally over 10 min.

a,



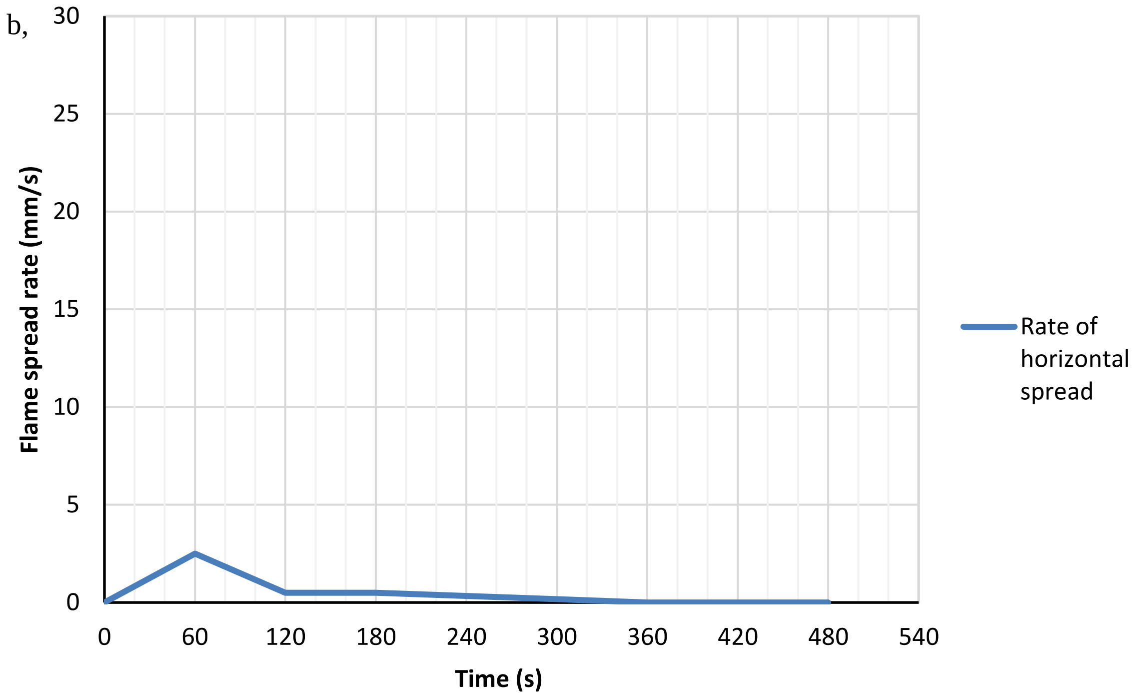
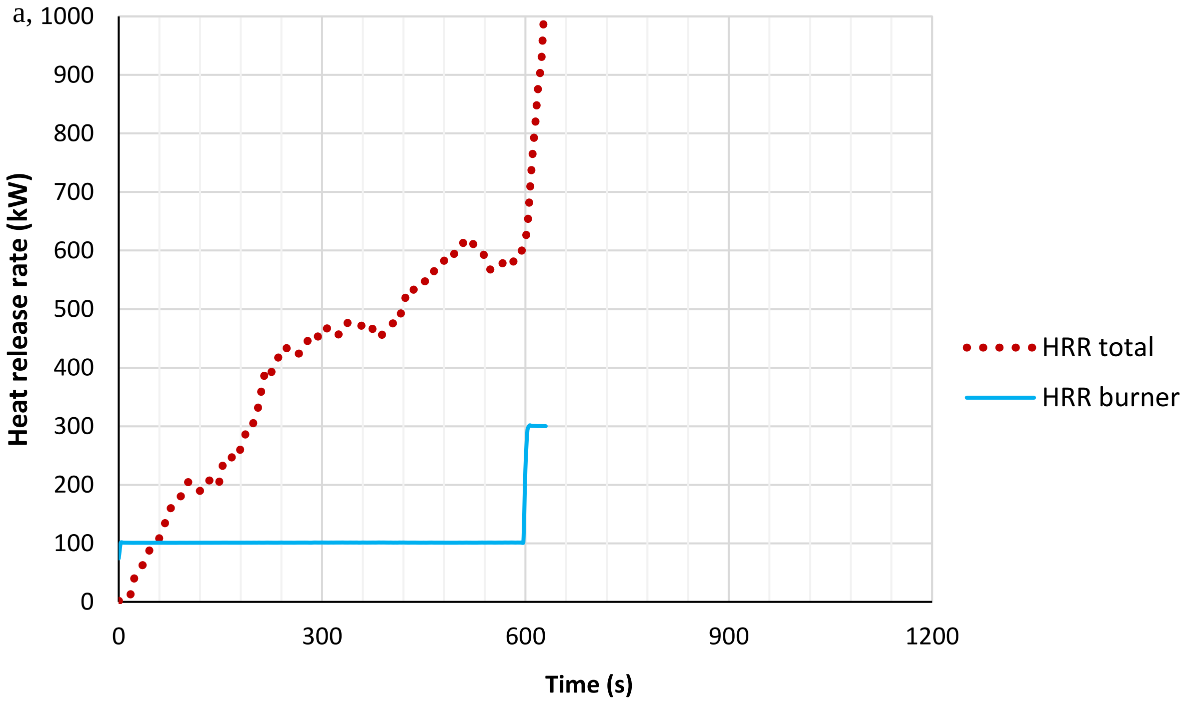


Figure 6.11. Experiment 3, (a) rate of heat release, (b) flame spread rate and extent of flame spread.

6.4.5 Experiment 4 – Upper Walls

In Experiment 4 the flames spread most rapidly along the top 400 mm of the walls, with a peak flame spread rate of 8–10 mm/s (Figure 6.12(b)). The rate of change of flame spread began to increase after 3 min After 5 min, the flames had reached across the short wall and most of the opposite wall.



b,

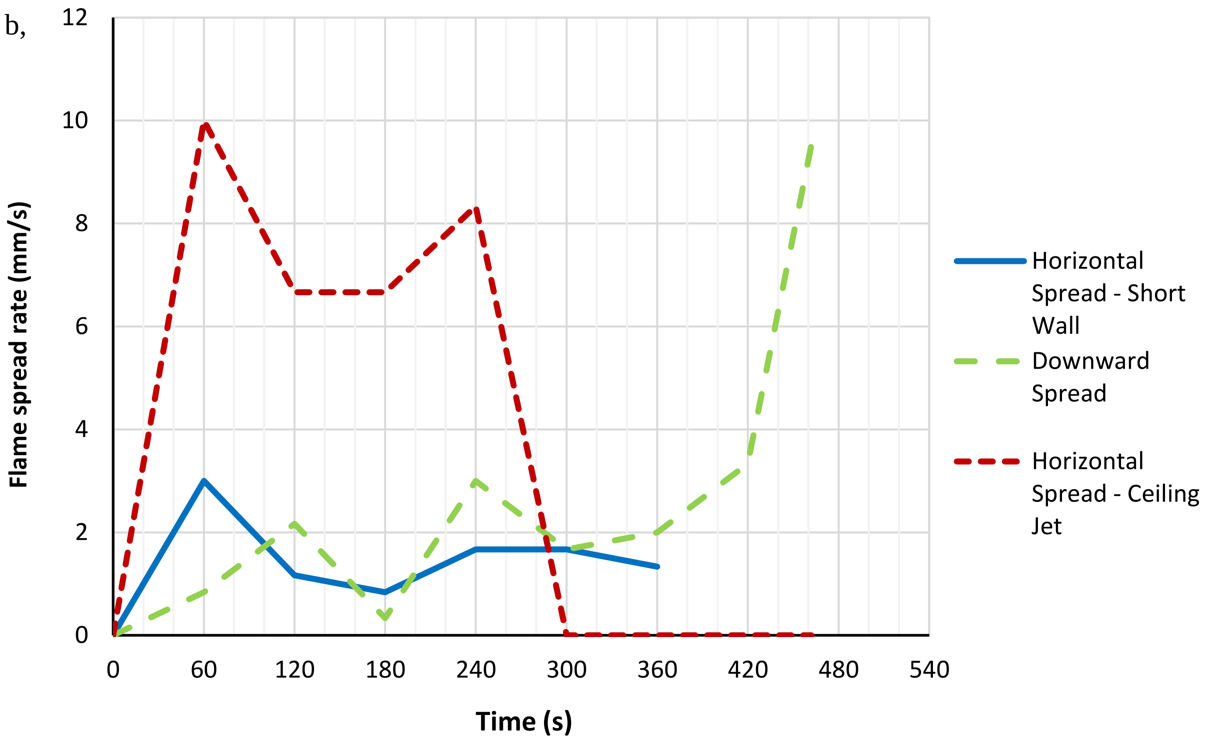


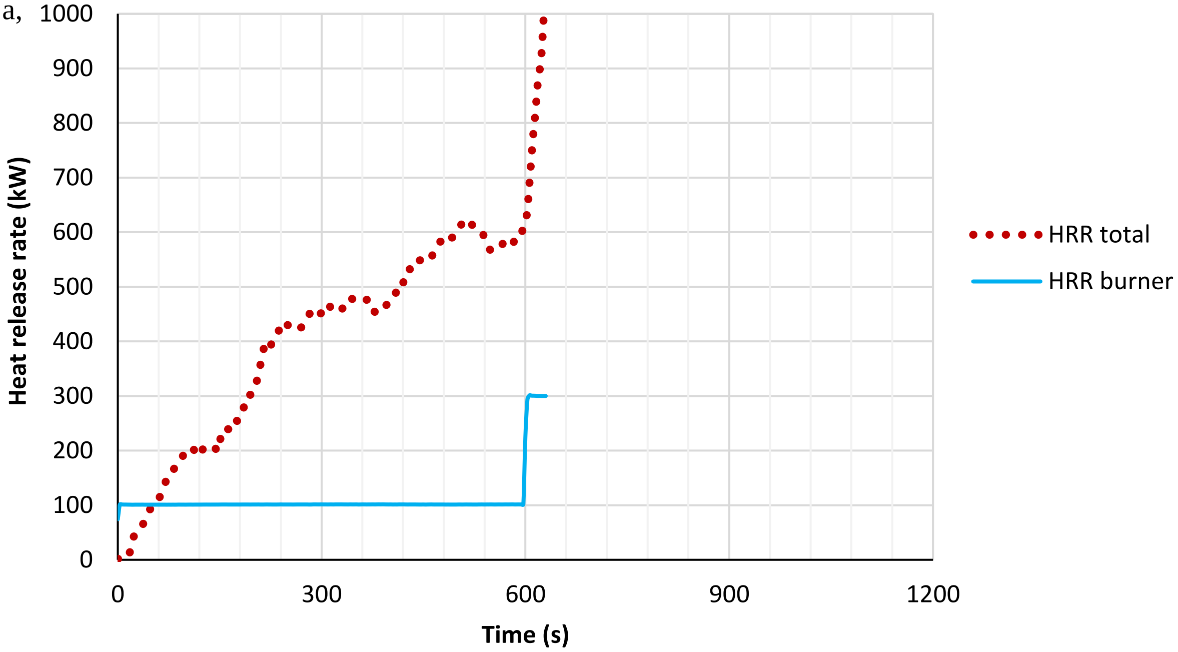
Figure 6.12: Experiment 4, (a) rate of heat release, (b) flame spread rates.

At 6 min, measurements of horizontal spread along the back wall are not available due to being obscured by the flames moving down from the ceiling jet. At 7 min, downward spread increased rapidly, covering 400 mm in 40 s, (average speed 9.4 mm/s) as the effects of radiated heat from the opposite return wall increased the downward spread to fully involve the plywood on the back wall. The rate of heat release reached its peak value of 941 kW at 8 min (Figure 6.12(a)) once all the plywood was flaming and then decreased as the amount of available material reduced. It was observed that the plywood was completely consumed which may have prevented the flashover criteria being reached. A thicker plywood may have provided the additional fuel needed for the rate of heat release to exceed 1 MW.

6.4.6 Experiment 5 - Full height wall coverings to 2.4 m

The rate of increase in rate of heat release in Experiment 5 appeared to begin reducing once the upper 400 mm of walls were fully involved, with horizontal and downward spread being the remaining directions of flame spread. However, burning debris ignited the lower unburned parts of the wall and some vertical spread of flame occurred from 380 s to 400 s with an average rate of 22 mm/s (this was intermittent, therefore not included on Figure 6.13 (b)). At 10 min, when the burner output was increased to 300 kW, the back wall was not fully involved with the lower quarter of the wall uncharred. However, by 10 min 30 s, all of the plywood was fully involved

a,



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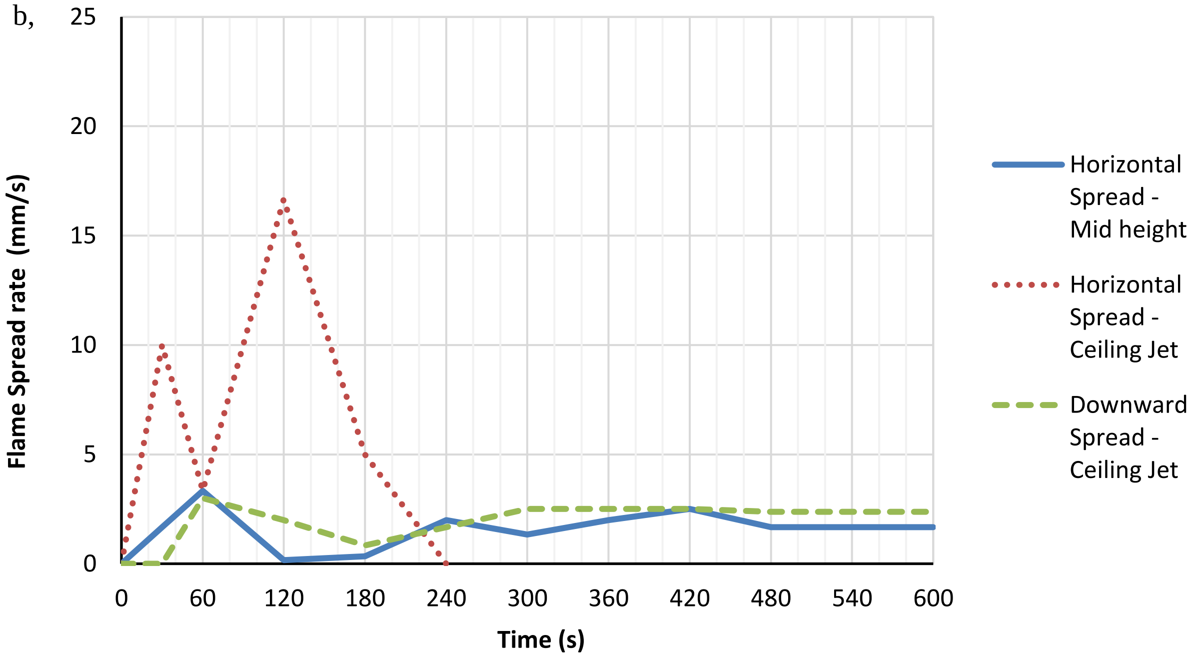
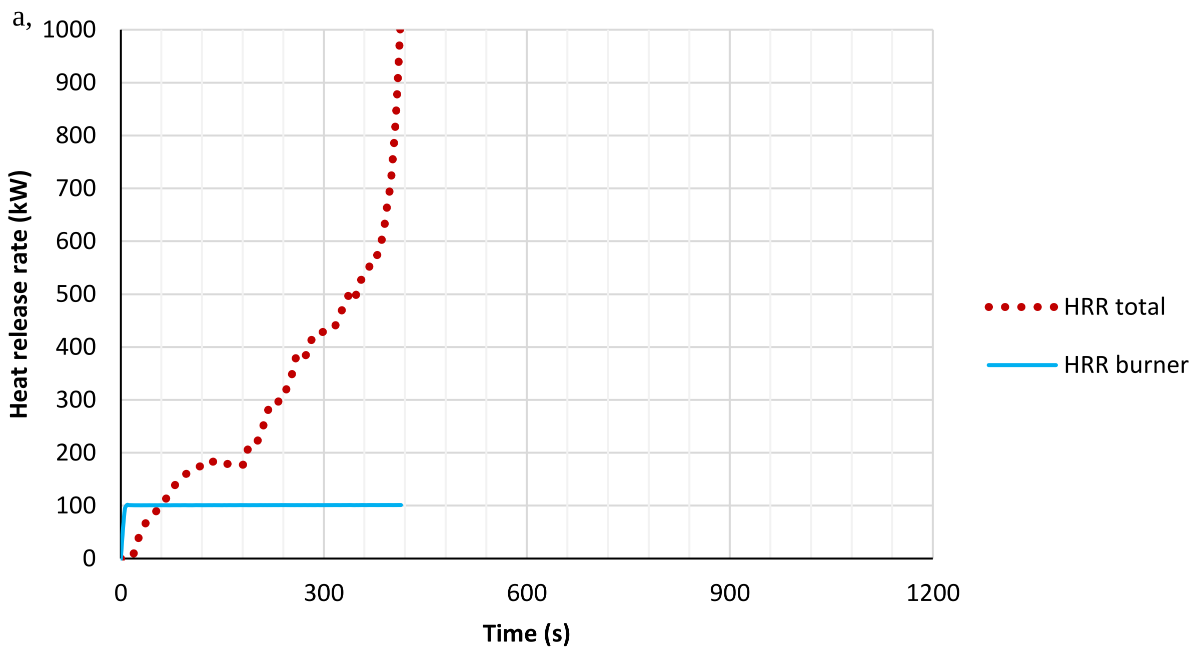


Figure 6.13: Experiment 5, (a) rate of heat release, (b) flame spread rate.

6.4.7 Experiment 6 - Full height wall covering to 3.6 m horizontally

Experiment 5 reached flashover at 630 s (Figure 6.13 (a)) whereas Experiment 6 reached flashover in 414 s (Figure 6.14(a)). Both experiments showed similar fire growth over the first 240 s, although Experiment 6 showed more rapid horizontal flame spread on the upper 400 mm of the wall (Figure 6.14 (b)) than in Experiment 5 whose ceiling jet travelled more slowly (Figure 6.13(b)).

The rate of heat release during the first 240 s of Experiment 6 grew very similarly to the same period in Experiment 2. During Experiment 6 after 270 s, however, the upper 400 mm of all of the walls were flaming, and flame spread occurred rapidly down the back wall (2.5–10 mm/s). This was possibly accelerated due to the combined radiation from the burner and the contribution from the flaming walls on both sides of the room. However, this spread is noticeably slower than the downward spread observed in Experiment 7, where the ceiling is present, and which achieved a downward flame spread of 7.5–10 mm/s between 300 s and 360 s.



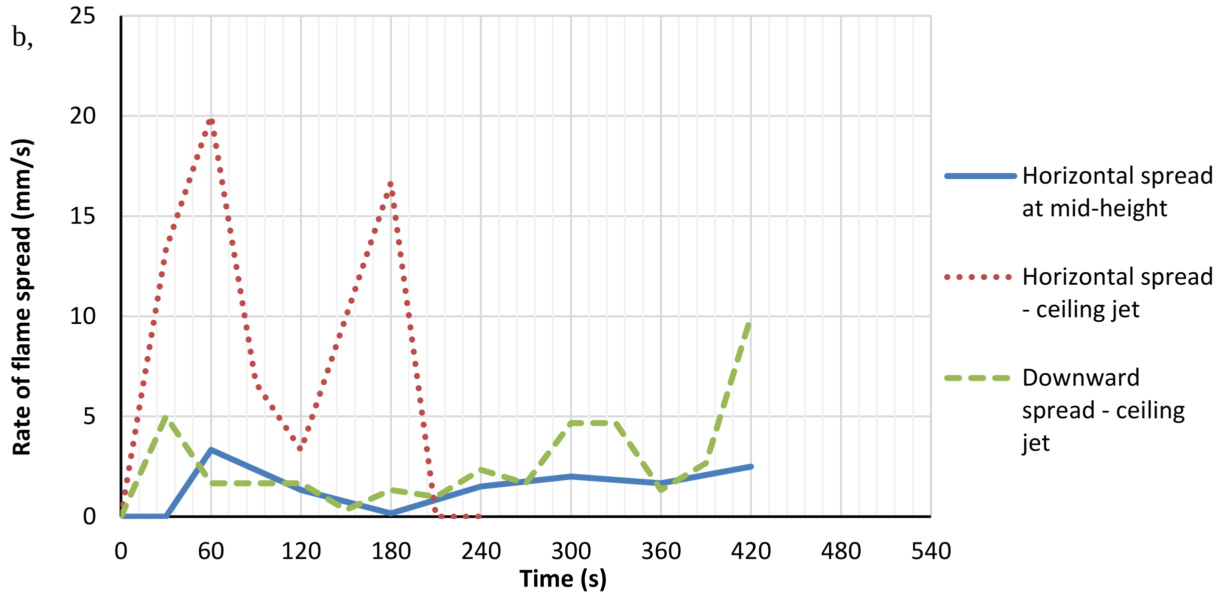
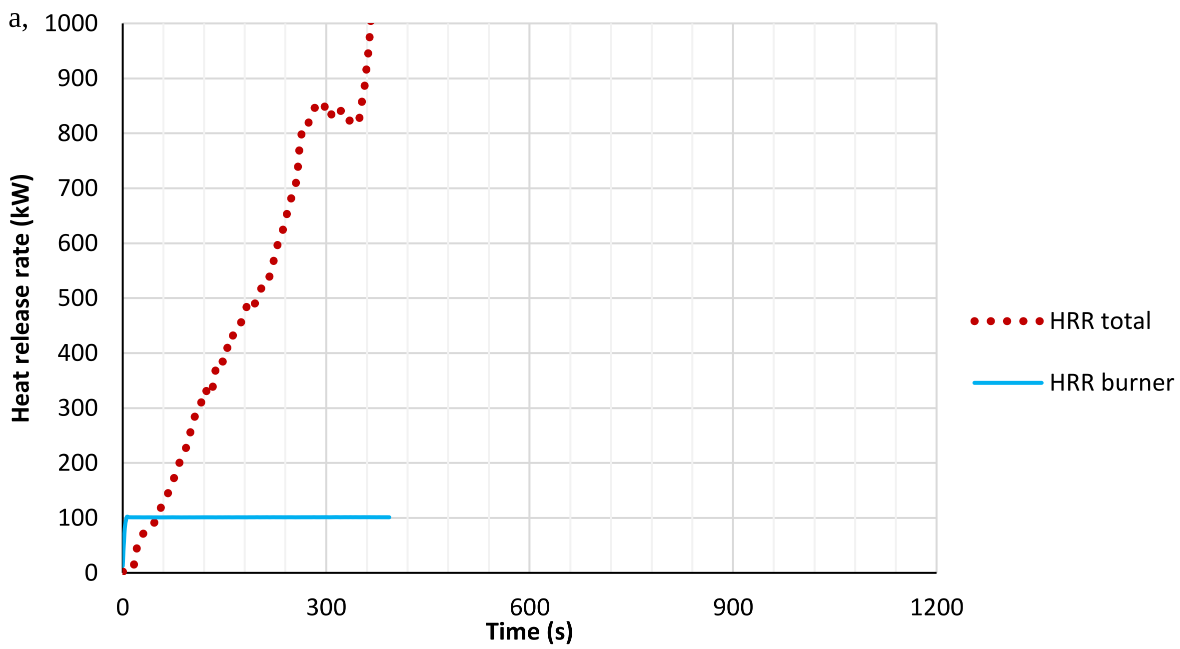


Figure 6.14: Experiment 6, (a) rate of heat release, (b) flame spread rate.

6.4.8 Experiment 7 - Ceiling with partial wall lining experiments

In Experiment 7, the lining on the walls provided a direct path for flame spread to advance vertically to the plywood ceiling. Flames had spread to more than 1.8 m along the ceiling by 2 min whereas this took 4 min in Experiment 3. The additional heat from the ceiling meant the entire upper walls to a depth of 500 mm below the ceiling were flaming after three minutes. For the next two minutes until t = 300 s downward flame spread (3–10 mm/s) then occurred faster than horizontal flame spread outwards from the burner (1–5 mm/s) (Figure 6.15(a)), until much of the wall was charred, causing flaming to reduce and rate of heat release decreased slightly. After 5 min, the flames spread onto the ceiling and the charred wall reignited due to the radiated heat downwards. Once the walls were fully involved again, the rate of heat release reached 1 MW after 366 s.



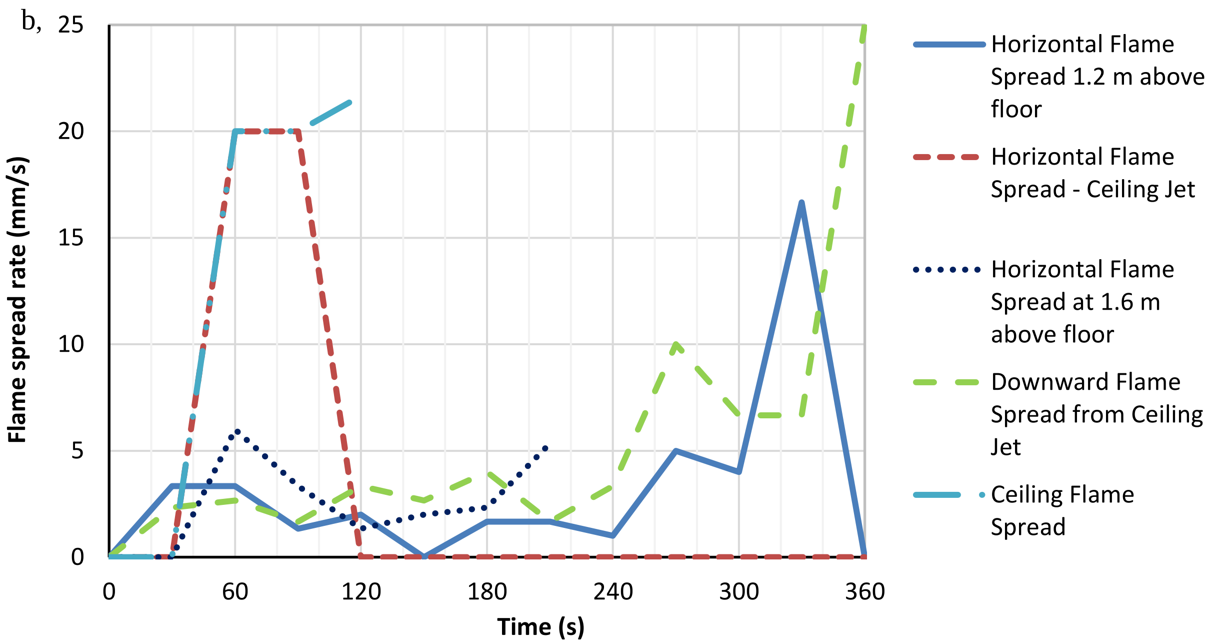


Figure 6.15: Experiment 7, (a) rate of heat release, (b) flame spread rate.

6.4.9 Ranking System

Two ranking systems are proposed and compared in Table 6.3. The time to flashover/peak HRR ranking system orders the experiments by the time to flashover (1 MW), however this is only applicable to Experiments. 1, 5, 6, and 7. Experiments 2, 3, and 4 which did not flashover are then ordered based on the time they took to reach their respective peak rate of heat release values.

Table 6.3: Ranking by experiment with most to least contribution to fire growth.

Time to flashover/peak HRR	1	7	6	5	4	2	3
FIGRA$_{RC}$	1	7	6	4	5	2	3

The experiments are also ranked according to the FIGRA$_{RC}$ value, as described in Section 2.4.1, where the highest FIGRA value is regarded as having a greater contribution to fire development. These gave a very similar ranking order to the time to flashover approach except that Experiment4 with only the upper walls lined is ranked as having a greater contribution than Experiment 5. The latter had the walls lined to full height to a width of 2.4 m. Even though Experiment 4 did not flashover, it did reach 941 kW, or very close to 1 MW. Comparing the rate of heat release curves of both experiments shows that the rate of heat release of Experiment 2 increased more rapidly than in Experiment 6. Using the FIGRA ranking system may be able to reduce the impact of an arbitrary rate of heat release at flashover on the comparision of surface linings.

It is important to note that the FIGRA$_{RC}$ correlation with the Euroclass ratings was not developed for partial linings so should be applied with care.

6.4.10 Summary of experimental observations

Experiment 4 had much more rapid horizontal flame spread away from the fire source than Experiment 3: Experiment 4 had a ceiling jet flame spread rates of 6-10 mm/s. while flame spread did not exceed 2 mm/s in Experiment 3. Experiment 4 also had peak rate of heat release (941 kW) that was 1.5 times greater than Experiment 3 (600 kW). Neither experiment reached flashover, however, which seems to indicate that although flashover is regarded as an unsurvivable condition, this may not be the best means to measure the effect of surface linings on the time available for occupants to egress from a space. In a real fire where the effect of room contents and egress distances influence the fire safety outcomes, the upper wall timber linings could still be expected to have a much more damaging effect than low level combustible linings.

The thickness of the plywood appeared to play a role in whether or not a scenario achieved a rate of heat release of 1 MW. Material thickness was important because in Experiments 2, 3, and 4, there was a noticeable decrease in rate of heat release as the plywood local to the burner flames was burned out before adjacent material sustained flame spread (Figure 6.16).

Figure 6.16: Burnout of the ceiling directly above the burner during Experiment 2 at 9 min 20 s.

It is proposed that thicker plywood would provide a greater mass of fuel closer to the burner and this would increase the rate of heat release during an equivalent experiment and possibly induce earlier flashover. It is possible that the predicted increase in rate of heat release when thicker timber is used could be offset by the thermally thick behaviour however this is not likely to be significant. Quintiere (1998) notes that for solids with a thickness of greater than 2 mm the time to ignition is not significantly affected.

Experiment 2 had the same total area of plywood installed in the room as Experiment 4 (8.64 m^2) However, even though Experiment 2 had more material located higher in the hot upper layer than in Experiment 4, Experiment 2 developed more slowly and reached a smaller maximum rate of heat release as the flames from the burner initially reached less of the combustible lining. This shows that the proximity of the ignition source to the lining was important to the rate of fire spread. Nevertheless, Experiments 5 and 6 showed that low level material can provide a path for flame spread to upper levels from low level ignition sources, even though Experiment 3 showed that low level plywood by itself made very little contribution to fire growth. The effect of creating a combustible path from the ignition source to the upper lining was observed again in Experiment 7, when the narrow path of plywood on the wall to the lined ceiling resulted in much more rapid fire growth, with 1 MW being achieved 2 min earlier than the peak rate of heat release (941 kW) of the ceiling only (Experiment 2) experiment.

7. B-RISK Modelling of Partially Lined ISO 9705 Experiments

7.1 Approach

The modified version of B-RISK was used to model the fire growth in the partially lined compartments tested in Section 7.4. The complete input files for each model are visible in Appendix A. The modelled enclosure measured 2.21 m in height by 2.4 m in width by 3.6 m in length. The configurations were generally input as per Approach 1 (see Chapter 5.2) where a maximum x-limit for horizontal extent of partial linings was specified, as was a y-limit denoting the maximum vertical limit. This was possible as in all configurations, except for Experiment 4, the timber lining extended to the same length from either side of the burner, and are continuous from floor level. However, the configuration in Experiment 4, where only the upper walls are lined, is discontinuous from floor level. Therefore, this was modelled using Approach 2, where a percentage of combustible wall lining (in the case of Experiment 4, the upper wall area equated 42 % of the total surface lining area) is specified, as well as the percentage of ceiling which includes combustible linings (in the case of Experiment 4, the ceiling is unlined so this is specified as 0 %).

Each model was run for 1200 s, even if flashover occurred earlier than this. There is no extinguishment mechanism included in the simulations, therefore the fire grows and delays in relation to the available fuel and ventilation. Data is recorded every 1 s.

7.2 Characterisation of the burner

The ignition source was a propane-fuelled gas burner in the corner of the room. This was modelled as a gas burner measuring 170 mm by 170 mm by 145 mm high. The heat release rate was input as 100 kW for the first 600 s of each simulation, followed by 300 kW for the following 600 s.

7.3 Characterisation of the flame spread properties of internal linings

Materials in the B-RISK flame spread model are characterised using results from the cone calorimeter, and the LIFT testing. Table 7.1 summarises the model inputs related to flame spread used by the B-RISK model, including density, specific heat and thermal conductivity as derived from earlier LIFT testing conducted by Quintiere et al. (1985).

In this study, LIFT equipment was not available for testing so the flame spread parameter, and minimum surface temperature for spread were characterised using values obtained from the literature, described below. The inputs from the cone calorimeter, which are the effective heat of combustion, the ignition temperature, and the critical FTP value for ignition, as well as a series of heat release curves to allow for extrapolation of the heat release of the burning lining, were found by cone calorimeter testing and are described in Section 5.

Table 7.1: Inputs for B-RISK model for 7 mm Plywood

Model input	**Value**	**Source**
Flame spread parameter (FSP) (kW^2/m^3)	7.4	(Quintiere & Harkleroad, 1985)
Minimum surface temperature for spread (°C)	170	
Thermal conductivity (W/mK)	0.12	
Specific Heat (J/kgK)	1215	
Density (kg/m^3)	523	
Effective heat of combustion (MJ/kg)	13.3	Cone data
FTP for ignition ($s(kW/m^2)^{(1/0.56)}$)	11642	Cone data

7.3.1 Flame Spread Parameter and Minimum Temperature for Flame Spread

The flame spread parameter is a factor used to derive the rates of opposed flow spread which are used to model downward and lateral flame spread. The flame spread parameter is derived from the ASTM E 1321, or the Lateral Ignition and Flame Transport (LIFT) apparatus as described in Section 2.2.3.6. There are a number of studies using plywood in LIFT experiments, including work by Huynh (2003) who undertook a review of existing LIFT data and observed that the range for flame spread parameters for plywood spanned from 2.79 to 48.6 kW^2/m^3. For this study, the flame spread parameter was obtained from Quintiere and Harkleroad (1985) for 6.3 mm thick pine plywood, as this plywood most closely resembled the 7 mm thick plywood tested in this study as it had similar thickness and density, and was the same species. Similarly, the minimum temperature for spread, thermal conductivity, density and specific heat were used from the same study (Quintiere & Harkleroad, 1985) to ensure that the values were realistic, as some values relate to one another, such as the inversely proportionate relationship between density and specific heat capacity.

The calcium silicate backing is also characterised in B-RISK, using test results for its performance at 200°C (Table 7.2). It is not characterised using cone data, as it is not combustible and contains no organic matter so flaming cannot be sustained on its surface, however, its thermal properties are important to characterise heat loss to the walls and ceiling, so these are summarised below.

Table 7.2: Input values for the 15 mm calcium silicate backing board.

Model input	Value
Flame spread parameter (FSP) (kW2/m^3)	0
Minimum surface temperature for spread (°C)	0
Thermal conductivity (W/mK)	0.12
Density (kg/m^3)	975
Specific Heat (J/kgK)	1250

7.3.2 Heat release rate for timber linings

A heat release rate per unit area curve for each external heat flux from the cone calorimeter experiments was provided as input data to B-RISK. The curves are interpolated within the B-RISK flame spread model to find the heat release rate of the burning surface lining once ignition has been established. Since the ignition times are input separately to calculate the ignition flux-time-product, it is recommended by (Wade, et al., 2013) that the heat release curves are input from when they reached 30 kW/m^2, at that this time is set as time = 0. The heat release rate curves were smoothed to reduce the input file size, as the data must be input at single time steps. The heat release rates are shown in Figure 7.1. These are used to calculate the heat release contribution from the burning surface lining as described in Section 4.1.

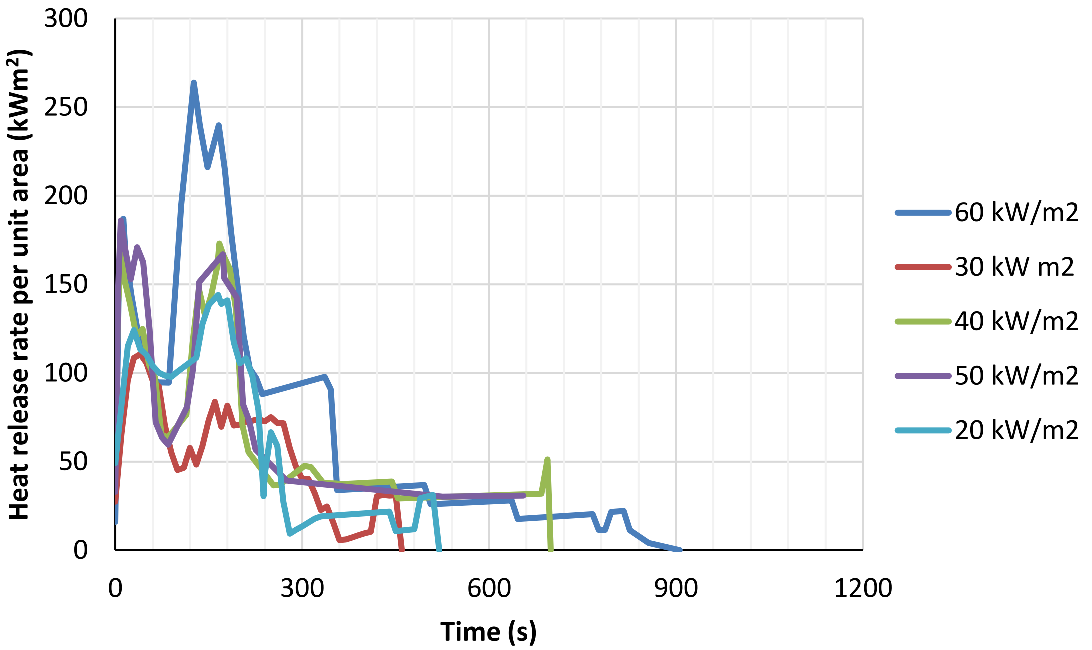


Figure 7.1: B-RISK input heat release rate curves, representative curve at each tested heat flux

7.4 Model results and comparison with experiments

7.4.1 Time to flashover and $FIGRA_{RC}$

Table 7.3 compares the times to flashover for the model and the experiments. As per ISO 9705, flashover is taken to be when the total rate of heat release including the burner reaches 1 MW, as stipulated by ISO 9705.

Table 7.3 Time to flashover for model and experiment

	Time to Flashover (s)						
Experiment	1	2	3	4	5	6	7
Model	146	676	767	204	206	204	136
Experiment	174	No FO	No FO	No FO	630	413	366

In Experiments 2, 3 and 4, the model predicts flashover when no flashover occurred in the experiments. The predicted time to flashover is the most accurate for Experiments 6 and 7, which have the greatest area of plywood lining (after Experiment 1). Overall, the model consistently predicts earlier flashover than what occurred in the experiments. Further this is always accompanied by very rapid predicted fire growth after the rate of heat release reaches about 500 kW. A surprising feature is that flashover is predicted 10 s earlier in Experiment 7, with only partially lined walls and ceiling, than in the fully lined Experiment 1.

Table 7.4 $FIGRA_{RC}$ for model and experiments.

	$FIGRA_{RC}$						
Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Model FIGRA	6.16	1.04	0.91	4.41	4.37	4.41	6.62
Experiment FIGRA	5.17	0.70	0.25	1.73	1.11	2.17	2.46

Table 7.4 shows the $FIGRA_{RC}$ values for the model, compared to the $FIGRA_{RC}$ values for the experiment. Not surprisingly, the model has considerably higher $FIGRA_{RC}$ values. However, Table 7.5 shows that the ranking of the tests by FIGRA, are reasonably similar; the major difference is that Experiment 7 ranks higher than the fully lined Experiment 1

Table 7.5: Ranking of Model and Experiment by $FIGRA_{RC}$ value

Ranking System	**Test Number (largest $FIGRA_{RC}$ value to smallest $FIGRA_{RC}$ value)**					
Model	7	1	4/6	4/6	5	2	3
Experiment	1	7	6	4	5	2	3

7.4.2 Measured and predicted heat release rate, upper layer temperature and layer height

Figure 7.2 shows a heat release rate comparison between the experiment and the B-RISK simulations for the fully-lined compartment experiment in which there is a good agreement. This is consistent with the findings of Dowling et al. (1999) and Wade (2013).

a,

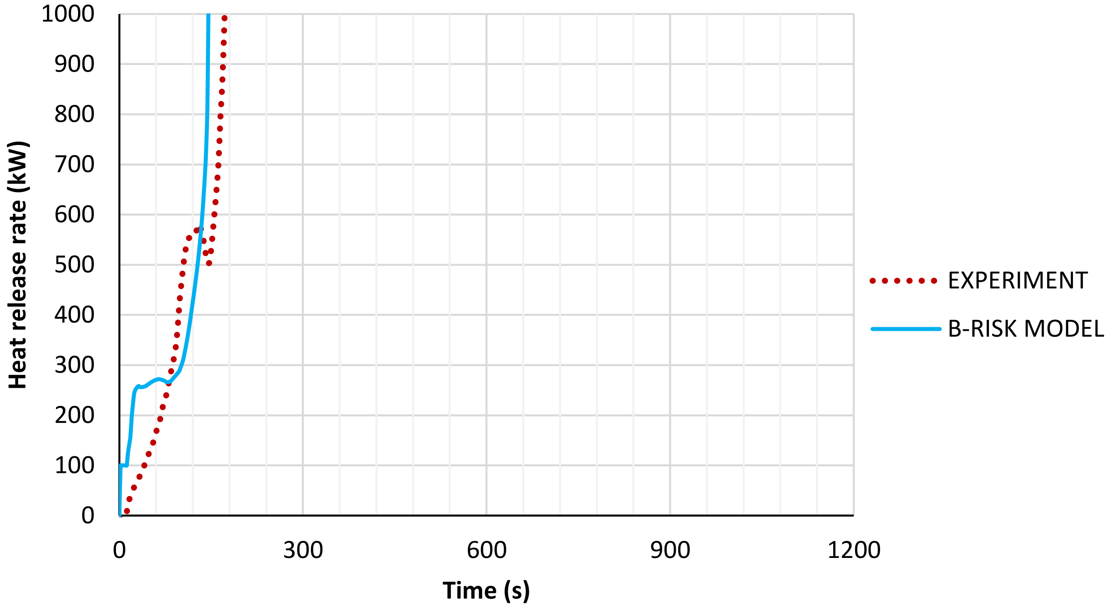


Figure 7.2: Measured and predicted heat release rate curve for Experiment 1.

b,

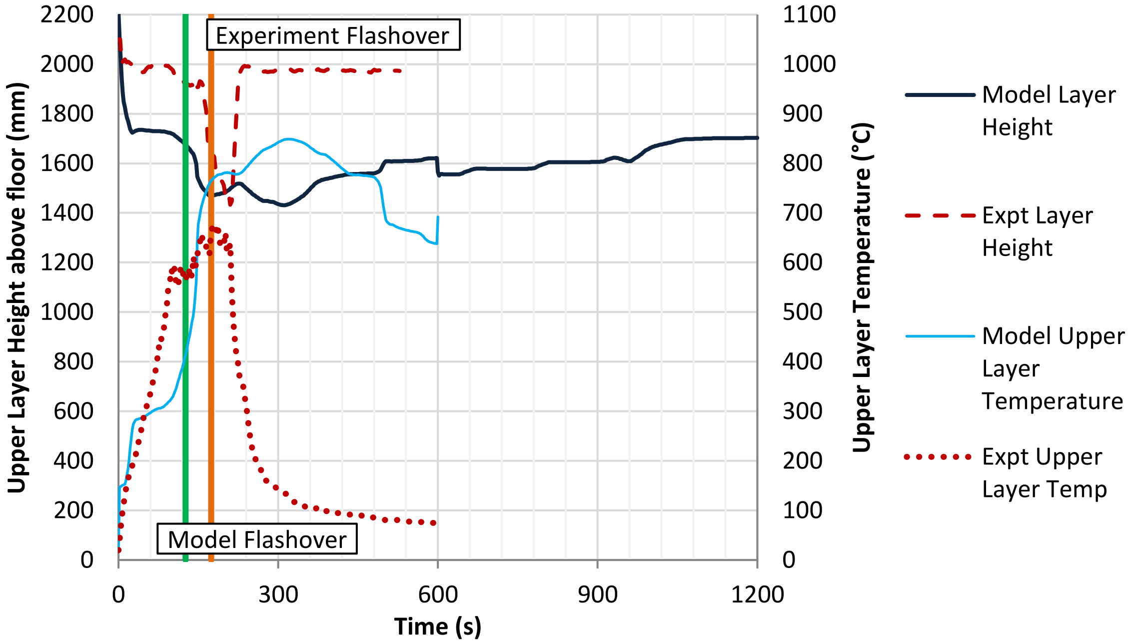


Figure 7.3: Measured and predicted upper layer height and temperature for Experiment 1.

Figure 7.4 to Figure 7.15 show the heat release rate comparison between the experiments and the B-RISK simulations for the six partially lined room experiments, as well as comparisons between the simulated and experimental upper layer heights and temperatures. There were several experiments where the total heat release rate did not reach 1 MW where B-RISK predicted flashover (Experiment 2, 3 and 4). However, Experiment 4 came very close to flashover with the peak rate of heat release exceeding 900 kW. The predicted heat release rate showed reasonably good agreement with Experiment 3 during the first ten min of the test, after which point the model showed a rapid increase in heat release rate, and reached flashover after 767 s whereas no flashover occurred in the experiment.

The only period when B-RISK significantly underestimates the heat release rate compared to the experiment is during the first five min of Experiment 2 when a maximum difference of 204 kW occurs at 435 s (**Figure 7.4: Measured and predicted heat release rate curve for Experiment 2.**Figure 7.4). Once the burner is increased to 300 kW, the heat release rates increase rapidly in both the model and experiment and show very good agreement. However, the model does not represent the total burnout of the timber on the ceiling and predicts flashover at 676 s. The rate of increase of heat release during the experiment begins to decrease after 672 s and only reaches a peak heat release rate of 809 kW after 723 s.

The experimental layer heights and temperatures are shown on each graph until the thermocouple data was no longer recorded during that experiment. This generally occurred either at 1200 s, or after flashover occurred (in those experiments where flashover was reached) and the sprinkler was activated to extinguish the fire. The full thermocouple data has been included on the graphs to show the effect of the sprinkler on the upper layer temperature to provide some indication of how well the experimental layer height approximation (using NFPA 92B as described in Section 6.2) could estimate the layer height. This was included because it is difficult to otherwise verify this approximation of the layer height, given that the observable smoke layer may not have necessarily aligned with the layer height described by the NFPA correlation as the smoke layer interface.

In general, the results of the approximation intuitively correlate to observable features during the test: the layer height drops prior to flashover, then there are distinctive decreases in upper layer temperature, and increases in layer height as the sprinklers are activated in Experiments 1, 5, and 6. The increase in layer height following sprinkler activation is less obvious in Experiment 7. It is not clear why this is so, but may have been as the layer did not drop significantly prior to flashover as the hot gases from the burning ceiling close to the doorway were able to flow out the door, rather than accumulate inside the space. Experiments 1, 5, and 6 had most of their fuel located around the burner corner, where hot gases could accumulate and form a more distinct layer before flowing out of the doorway. It must be made clear that after experimental flashover, it is not logical to compare modelled and experimental layer characteristics at all, as the effect of the sprinkler is not included in the B-RISK model.

A further notable characteristic of the experimental layer height approximation is that the experimental upper layer heights at t = 0 s are located lower than the topmost thermocouple at 2100 mm in

Experiments 2, 3, 4 and 5 This is attributed to a slight temperature gradient already present inside the space. This became more obvious in later experiments, with layer heights being recorded as approximately 2000 mm above the floor level (whereas the topmost thermocouple was at 2100 mm and the ceiling at 2200 mm). This is likely to have been because the tests were conducted in quick succession, and the room did not have adequate time to fully cool down. The calcium silicate substrate was re-used for each test, and retained heat from the earlier experiments, causing an artificial layer height at test start. B-RISK, by comparison, does not account for natural stack effect in the space thus assumes that the layer height is at the ceiling at t = 0 s.

The experimental and modelled layer heights show the best agreement in Experiment 1, where the modelled layer height is located within 300 mm below the experimental layer until flashover. In the partially lined experiments, B-RISK generally models the layer height 400 mm to 600 mm below the experimental layer height. This may be because B-RISK calculates the layer height based on McCaffrey's model plume entrainment model (Wade, et al., 2013), whereas the experimental layer height was defined (from NFPA 92) as the location where the gas temperature first reach 80% of the difference between maximum and minimum measured gas temperatures. It is also noted in previous studies such as (Rockett, 1995) that the McCaffrey correlation, as used by B-RISK has been shown to overestimate entrainment (and therefore underestimate layer height) in some cases but this is usually in taller enclosures. Lai et al. (2013) also conducted an investigation into the best method of estimating layer height in enclosure fires with an open vent (such as a door) and observed that airflows through the vent made the smoke layer temperature unstable, making the N-percentage method such as that used in the NFPA model here unreliable. It was also noted in the same study, which located six thermocouples throughout several two-room fire experiments, that the relative location of the thermocouple tree to ventilation, as well as to the fire source affected the calculated height of the smoke layer using the N-percentage method similar to NFPA 92. It was found that even when the thermocouple was located where the layer was observed, the thermocouple temperature readings were consistently not of the upper layer temperature (but could be attributed to radiant heat from the fire, or cooler air from the vents). This study concluded that using the N-percentage rule to find layer heights for thermocouples was less accurate, compared to observations, when thermocouple tree was located in the same room as the burner., rather than in an adjacent room (Lai, Chen, Tsai, Tsai, & Lin, 2013). In summary, the layer height and temperature comparison in this study are included as an indicative means of comparing the model and experimental results, and the results of its comparison are limited in its accuracy.

Nevertheless, when the model and experimental layer temperatures are compared, Experiments 1 and 2 are the only two experiments where the experimental layer temperature significantly exceeds the model layer temperature.

In Experiment 1, the experimental layer temperature increased more rapidly than the layer temperatures calculated by B-RISK prior to model flashover at 146 s, or 28 s before the experimental flashover was observed. From 146 s until experimental flashover at 174 s (after which point in the experiment the gas flow to the burner was halted and the sprinkler activated) the model temperature increased more rapidly and exceeded the experimental layer temperature by more than 80°C.

In Experiment 2 where only the ceiling is lined the model upper layer temperature reaches 191 °C after 20 s, and then increases very slowly until it reaches 232 °C at 600 s. The experimental layer temperature increases much more rapidly, reaching 483°C after 399s, before cooling slightly to 245 °C at 600 s. Once the burner is activated at 600 s, the model and experiment upper layer temperatures increase similarly for a further 60 s. After this point, the model heat release rate reaches 1 MW (flashover) and the temperature rapidly increases to a maximum of 852 °C at 836 s. The upper layer temperature increases less rapidly, reaching a peak of 643°C at 819 s.

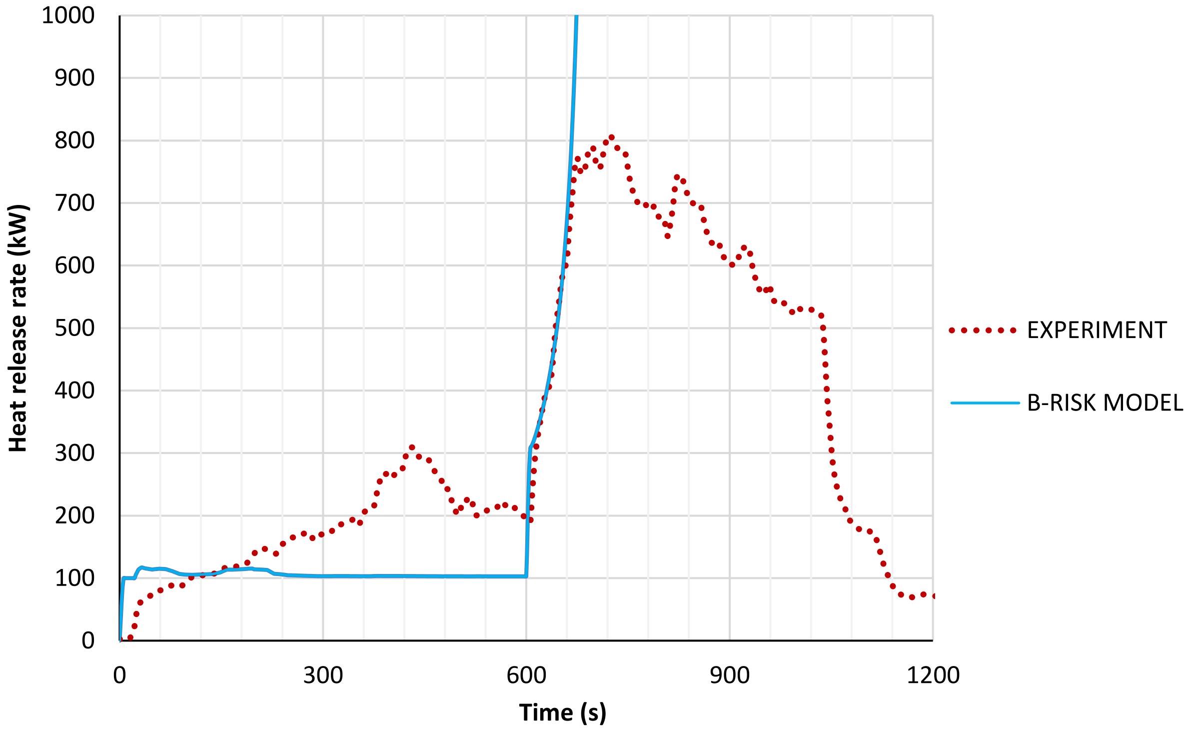


Figure 7.4: Measured and predicted heat release rate curve for Experiment 2.

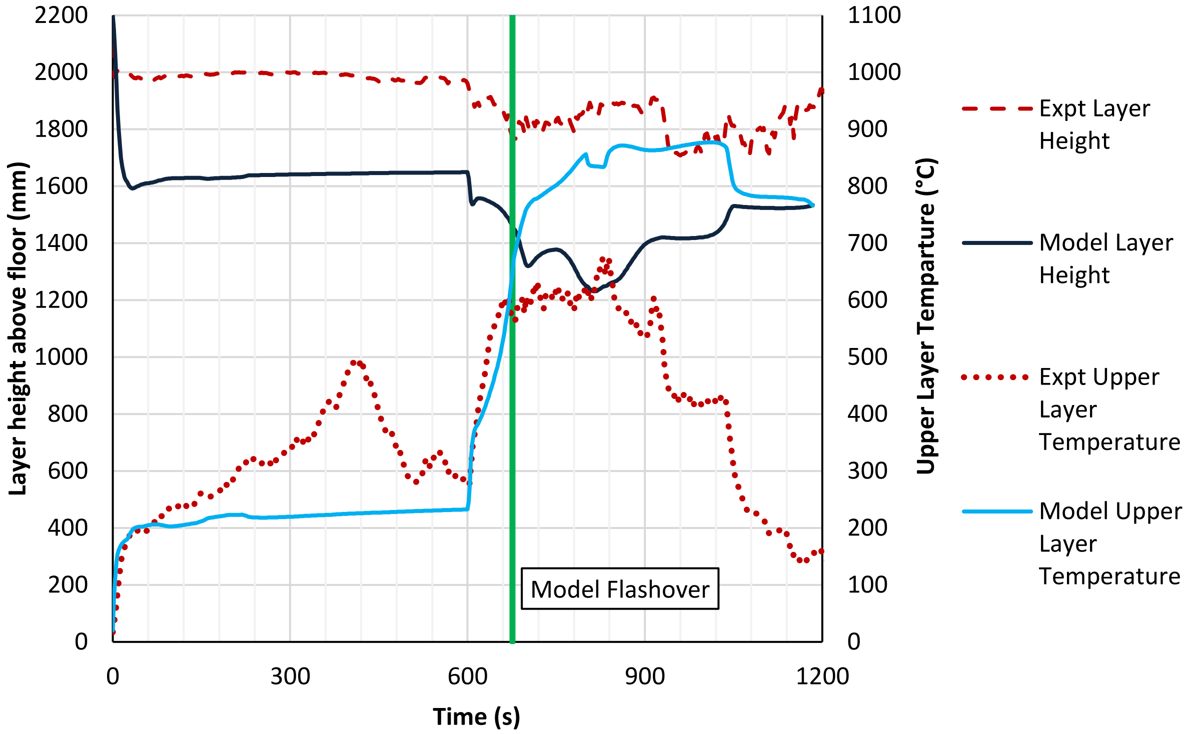


Figure 7.5: Measured and predicted upper layer height and temperature for Experiment 2.

In Experiments 3-7 (Figure 7.6 to Figure 7.15), the model layer temperatures are generally greater than those of the experiments. In the early stages of fire development prior to model flashover (which consistently precedes experimental flashover, if experimental flashover occurs), the model and experimental upper layer temperatures show good agreement, and are within 100°C of each other although the model temperatures are usually slightly higher than the experimental values. However, once the modelled upper layer temperature approaches 450 °C, then the model temperatures increase rapidly and coincide with flashover. The experimental upper layer temperatures increase less rapidly, and even at flashover, show less rapid (i.e. not vertical) temperature growth.

In summary, B-RISK is conservative in its model of the ISO 9705 partially lined experiments. B-ROSL consistently models flashover before flashover is observed experimentally, with runaway heat release and layer temperature increases occurring as the upper layer temperature approaches 450°C. Modelled layer temperature and depth show best agreement during the initial fire development, particularly in Experiments 1, 5, 6 ,7 where most of the combustible lining is located close to the burner.

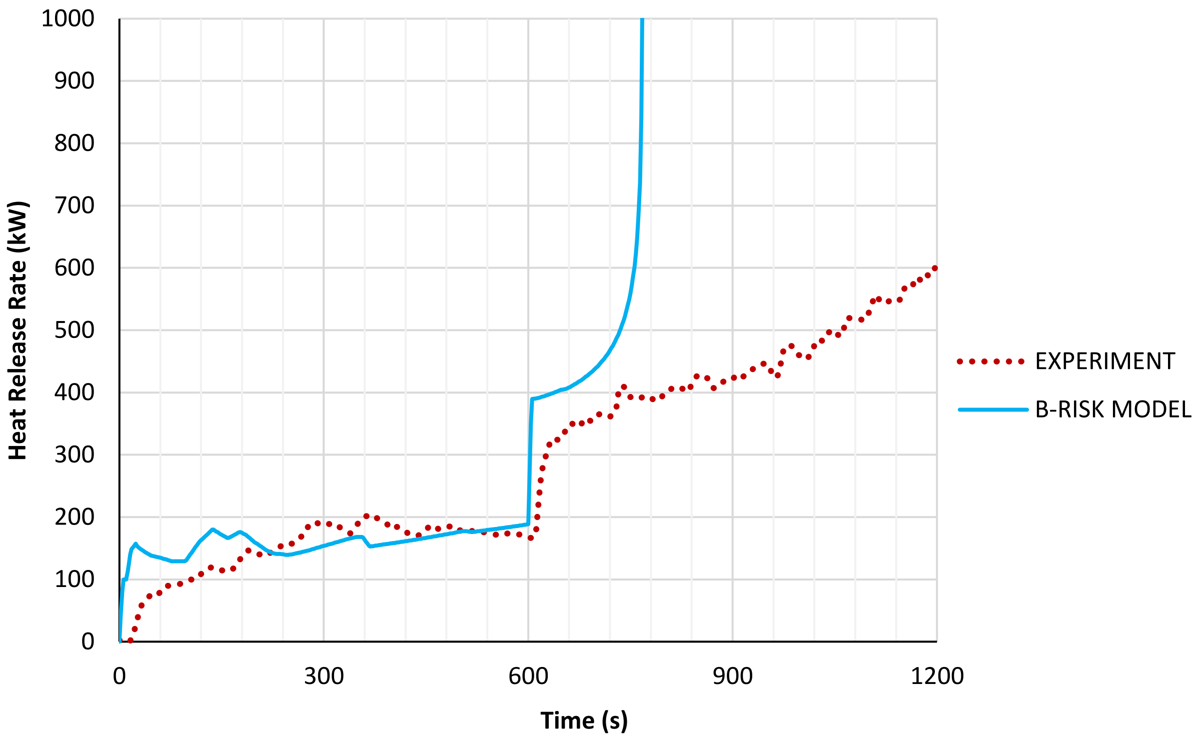


Figure 7.6: Measured and predicted heat release rate curve for Experiment 3.

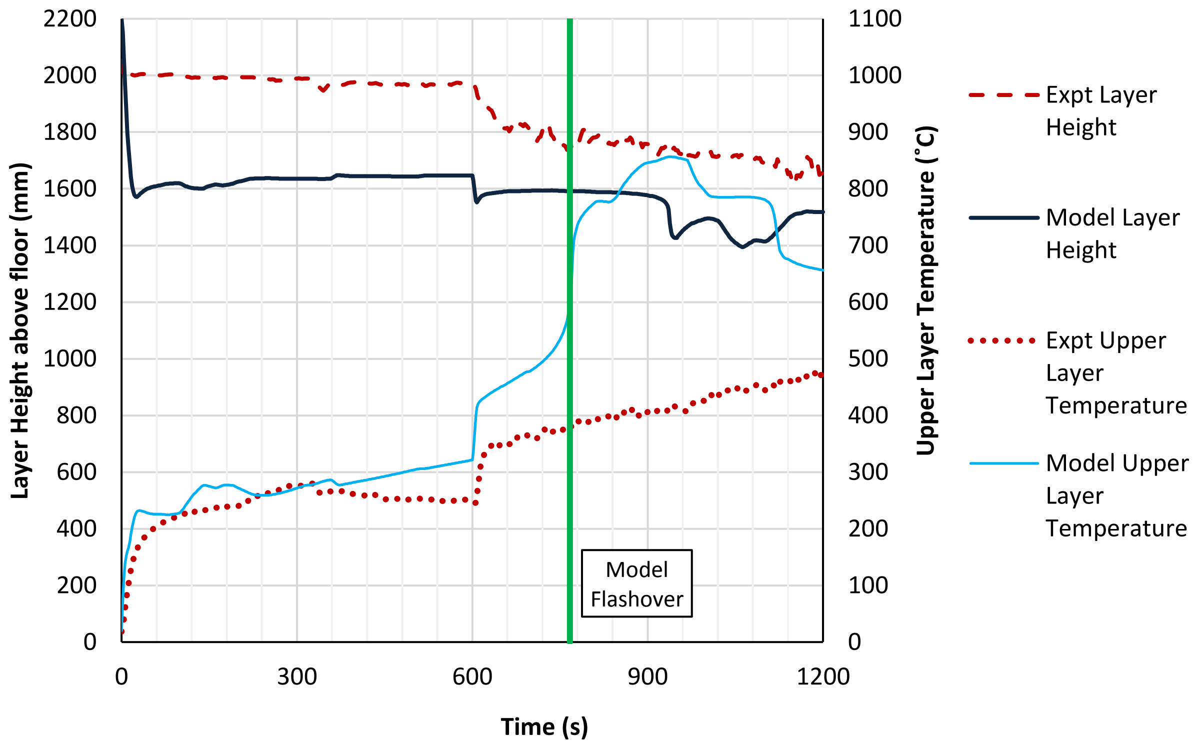


Figure 7.7: Measured and predicted upper layer height and temperature for Experiment 3.

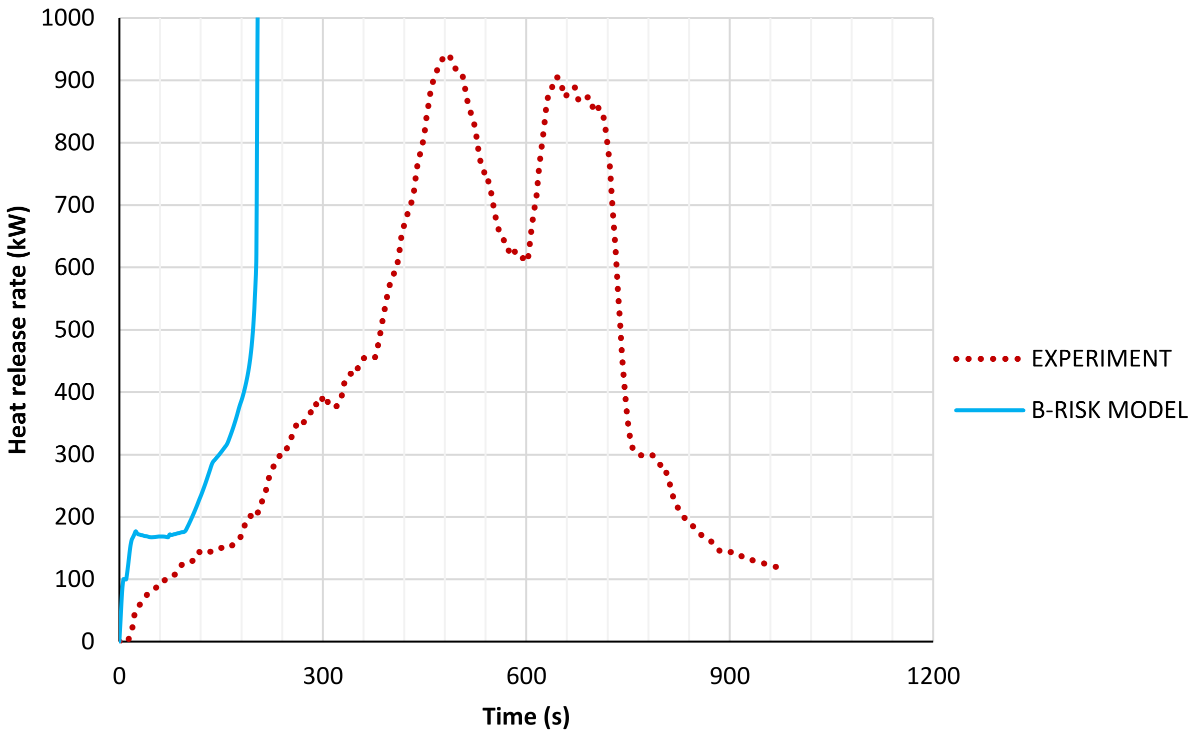


Figure 7.8: Measured and predicted heat release rate curve for Experiment 4.

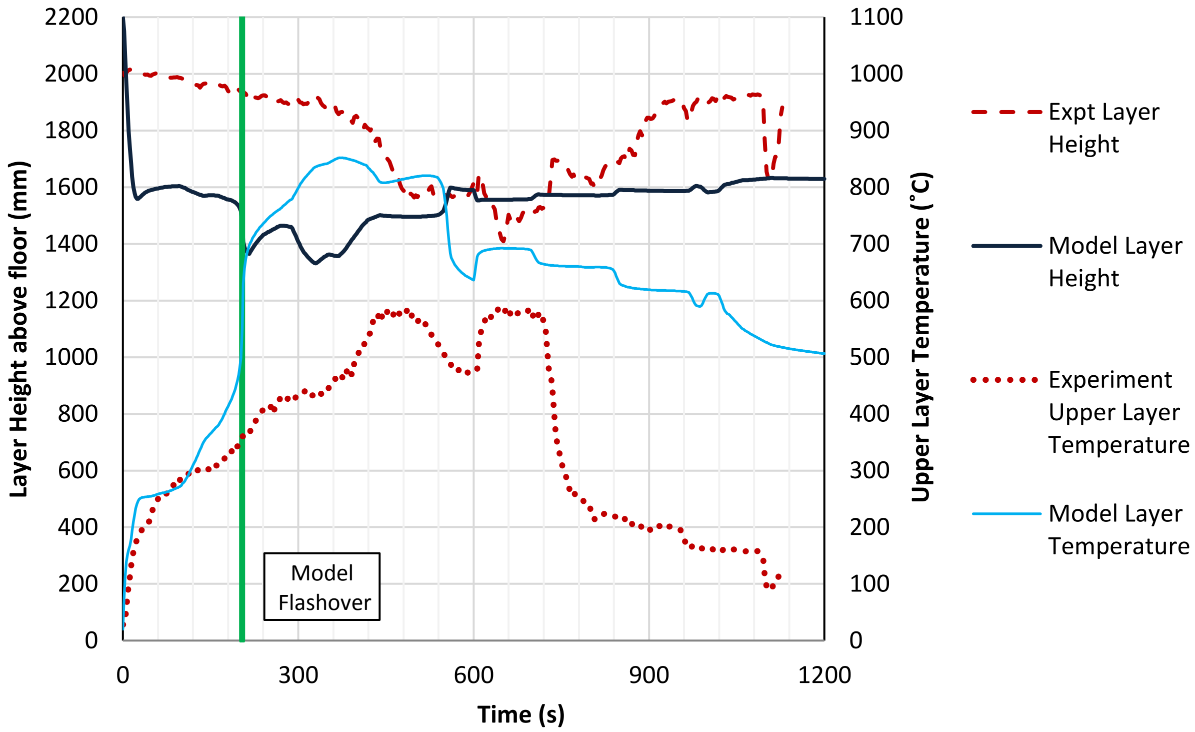


Figure 7.9: Measured and predicted upper layer height and temperature for Experiment 4.

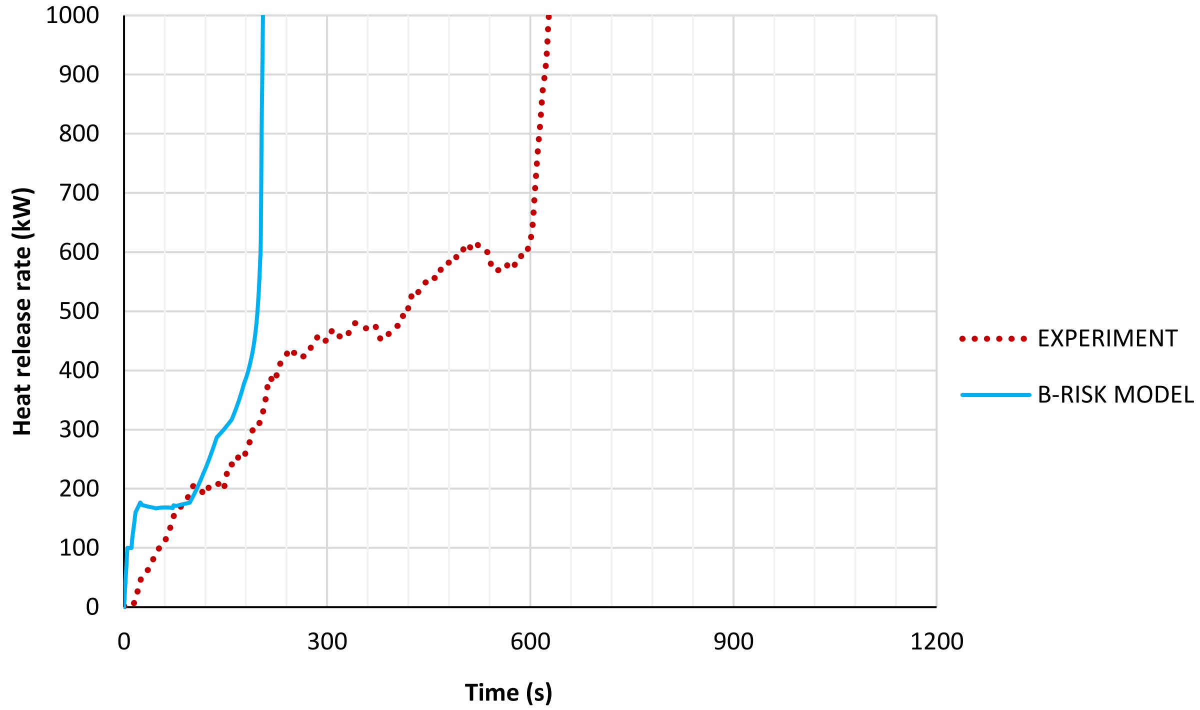


Figure 7.10: Measured and predicted heat release rate curve for Experiment 5

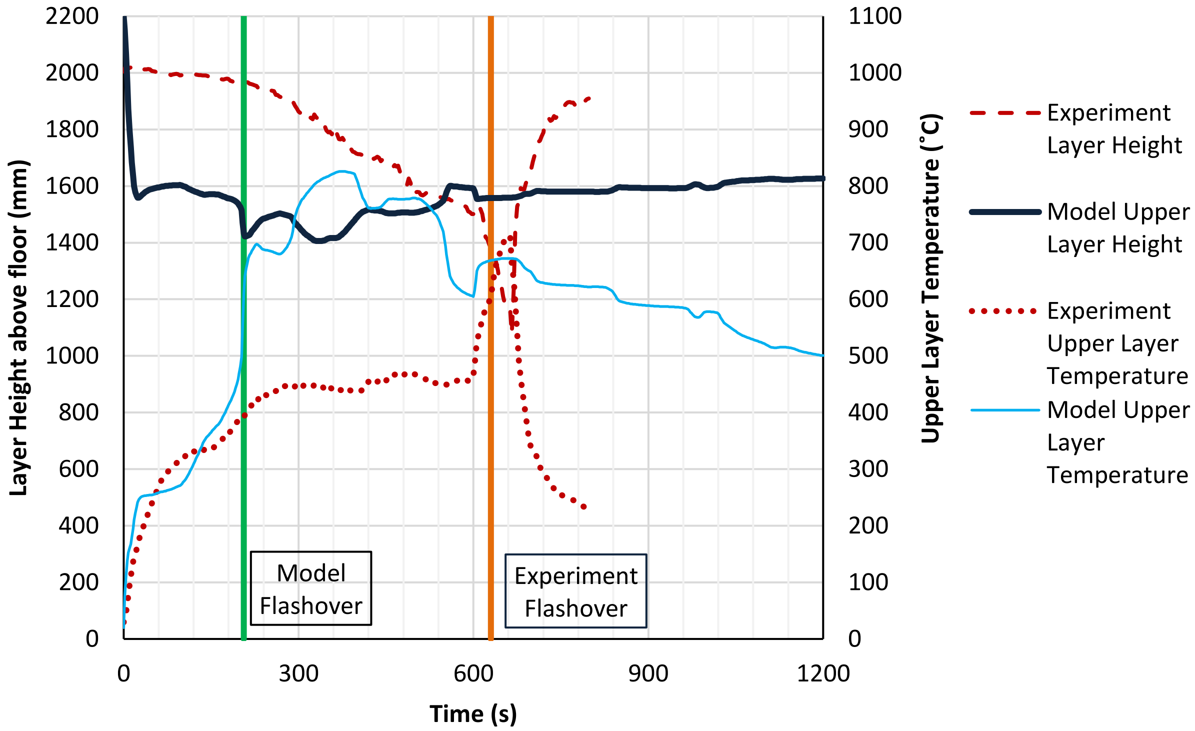


Figure 7.11: Measured and predicted upper layer height and temperature for Experiment 5.

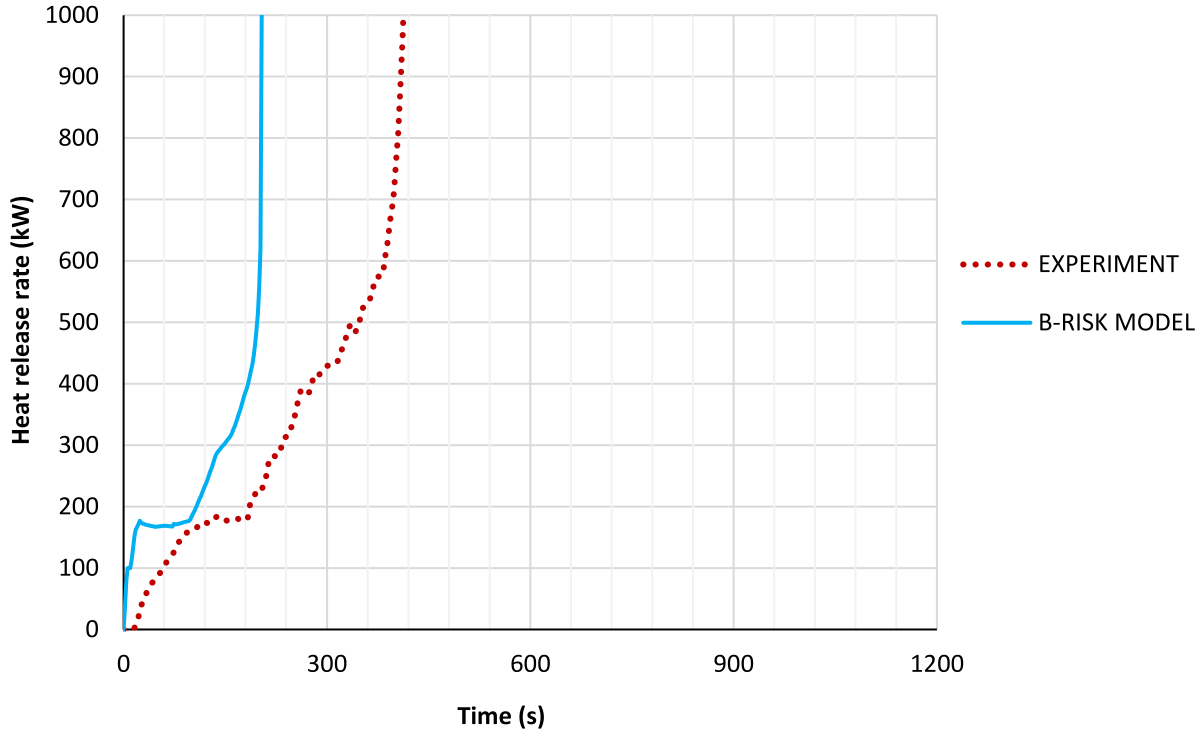


Figure 7.12: Measured and predicted heat release rate curve for Experiment 6.

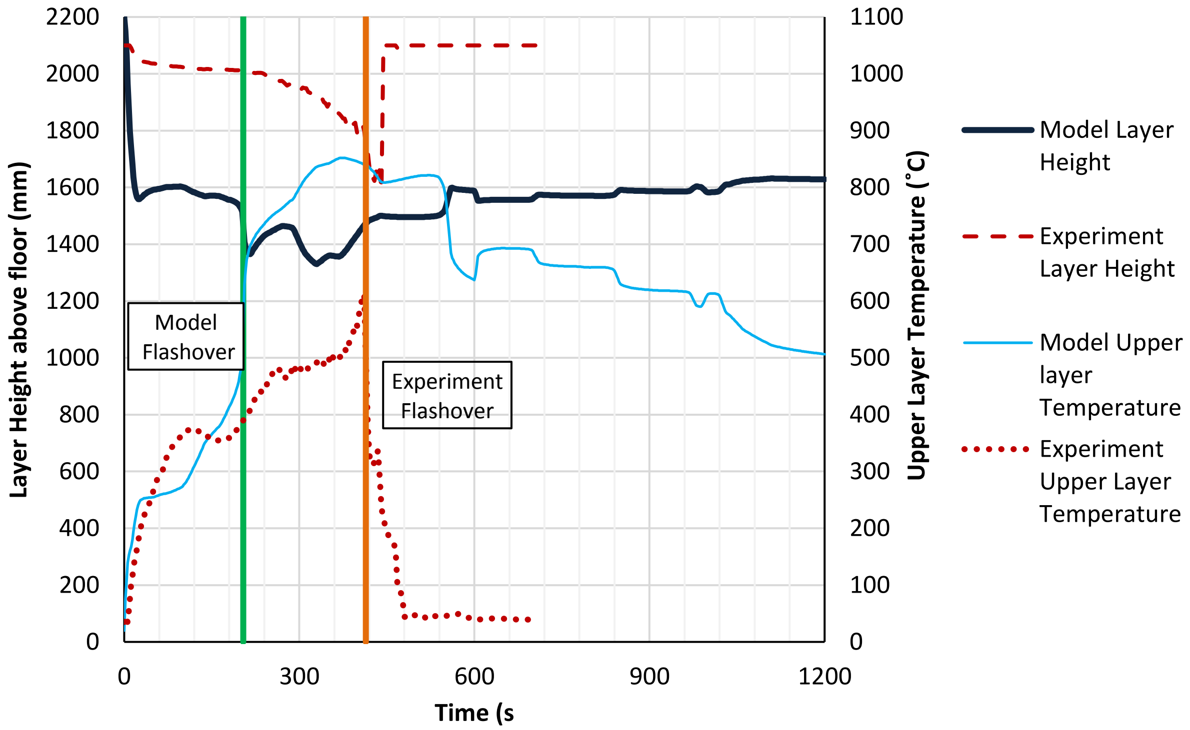


Figure 7.13: Measured and predicted upper layer height and temperature for Experiment 6.

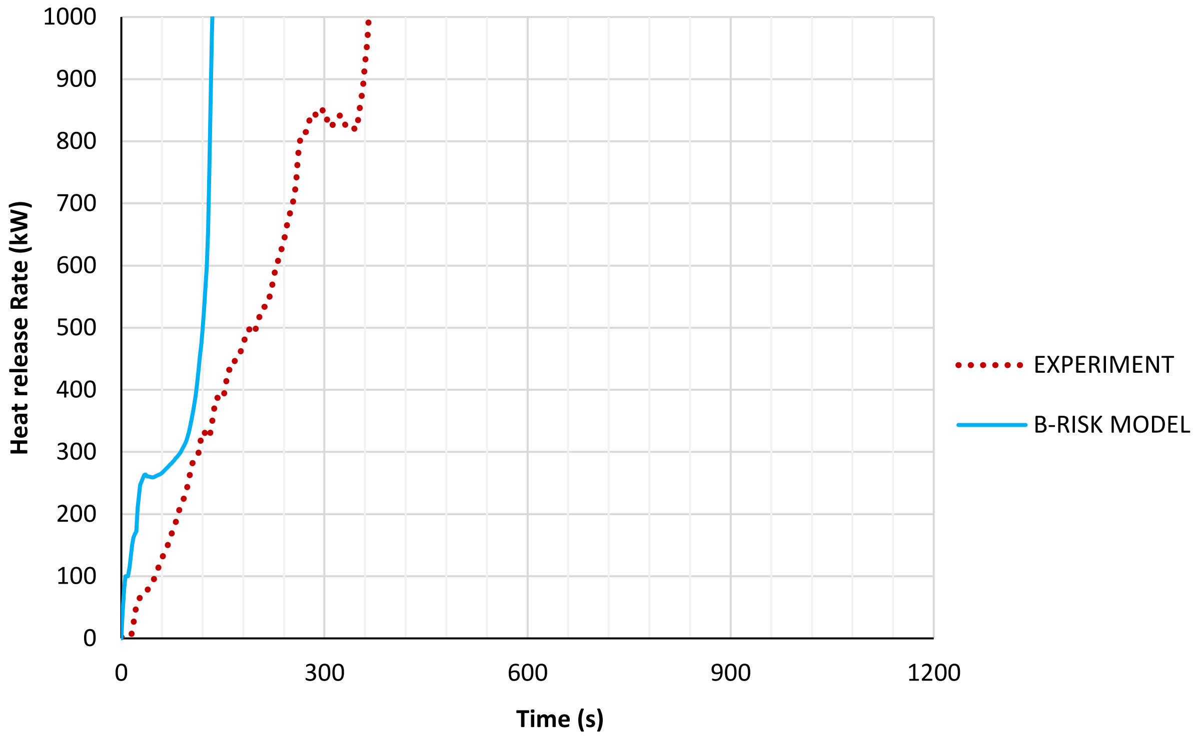


Figure 7.14: Measured and predicted heat release rate curve for Experiment 7

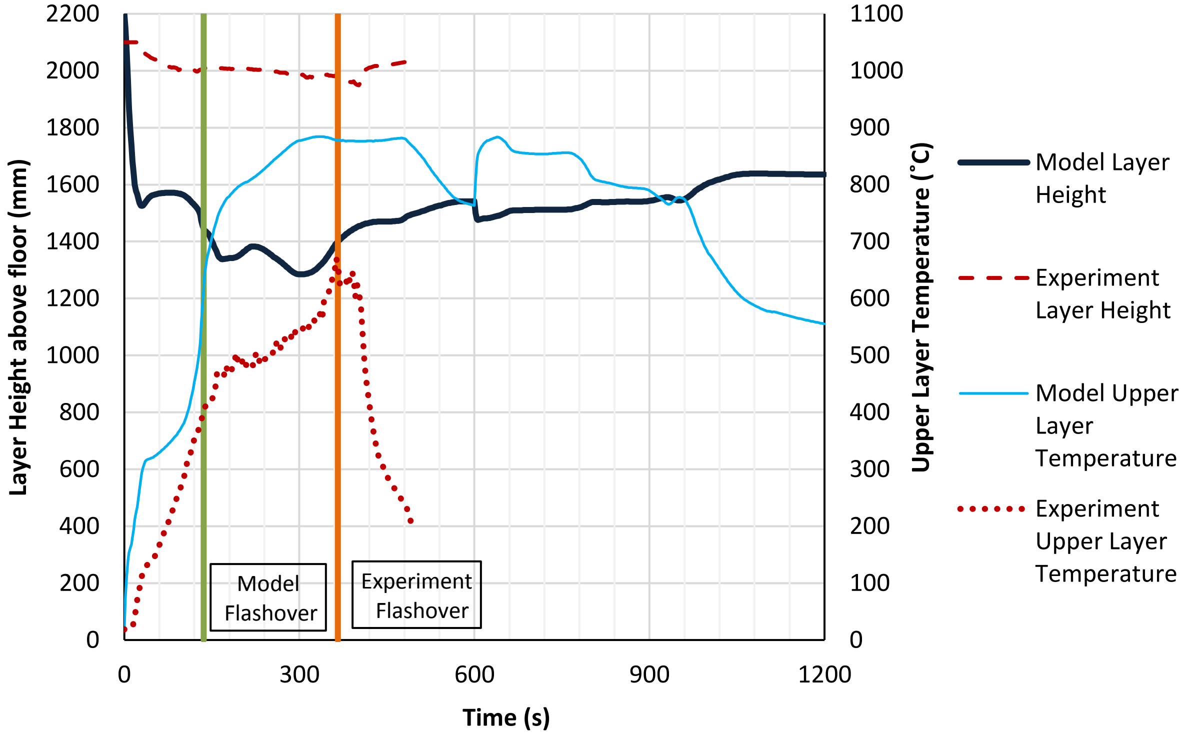


Figure 7.15: Measured and predicted upper layer height and temperature for Experiment 7.

7.5 Sensitivity

A sensitivity analysis is conducted on some of the data used to develop model parameters. This analysis includes the sensitivity of the model to the flame spread parameter, the minimum temperature for spread, and the plume entrainment rate.

7.5.1 Flame spread parameter

The model is generally not very sensitive to the flame spread parameter, which is used to predict the lateral rate of flame spread. For this study, the modelling is repeated with flame spread parameters of 20 kW^2/m^3 and 30 kW^2/m^3 and these results are compared with the original model using FSP of 7.4 kW^2/m^3. The results of varied flame spread parameters on Experiment 5 which are shown in Figure 7.16 shows only minor variation between trials, and this was the case for most of the experiments . However, the heat release rate in Experiment 3 (Figure 7.17), where the plywood is located on the bottom half of the wall does appear to be affected considerably by the flame spread parameter. This is most likely because this configuration has a greater proportion of lateral flame spread contributing to its fire growth, compared to Experiment 5, where the walls are lined to full height and upward flame spread is more important. Additional trials are included using FSP of 2.8 kW^2/m^3 for 20 mm thick plywood from Huynh (Huynh, 2003), and 13 kW^2/m^3 for 12 mm thick plywood from Quintiere (1998). While FSP of 13 kW^2/m^3 shows the best agreement with the experimental data for the first 10 min, the lower FSP values showed better agreement after 10 min, and delayed flashover. However, 'runaway' fire development is still observed at low FSP values, and therefore flashover is still predicted by B-RISK in these cases.

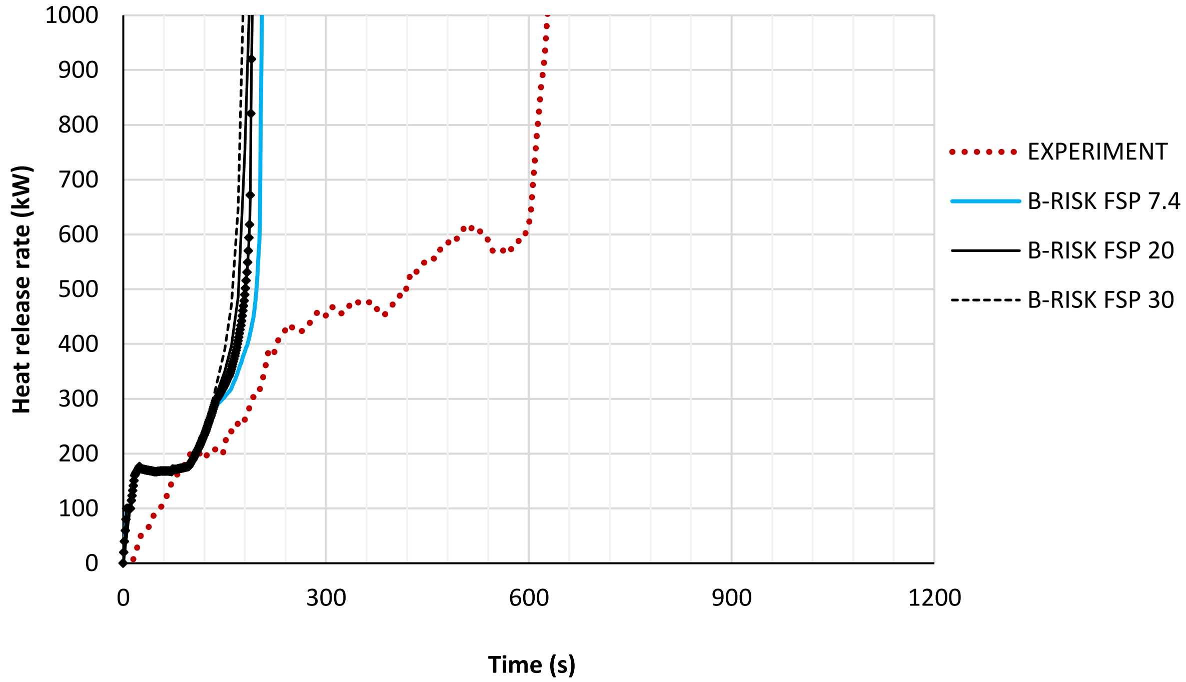


Figure 7.16: Modelled heat release rates for Experiment 5 using various flame spread parameter (FSP) values

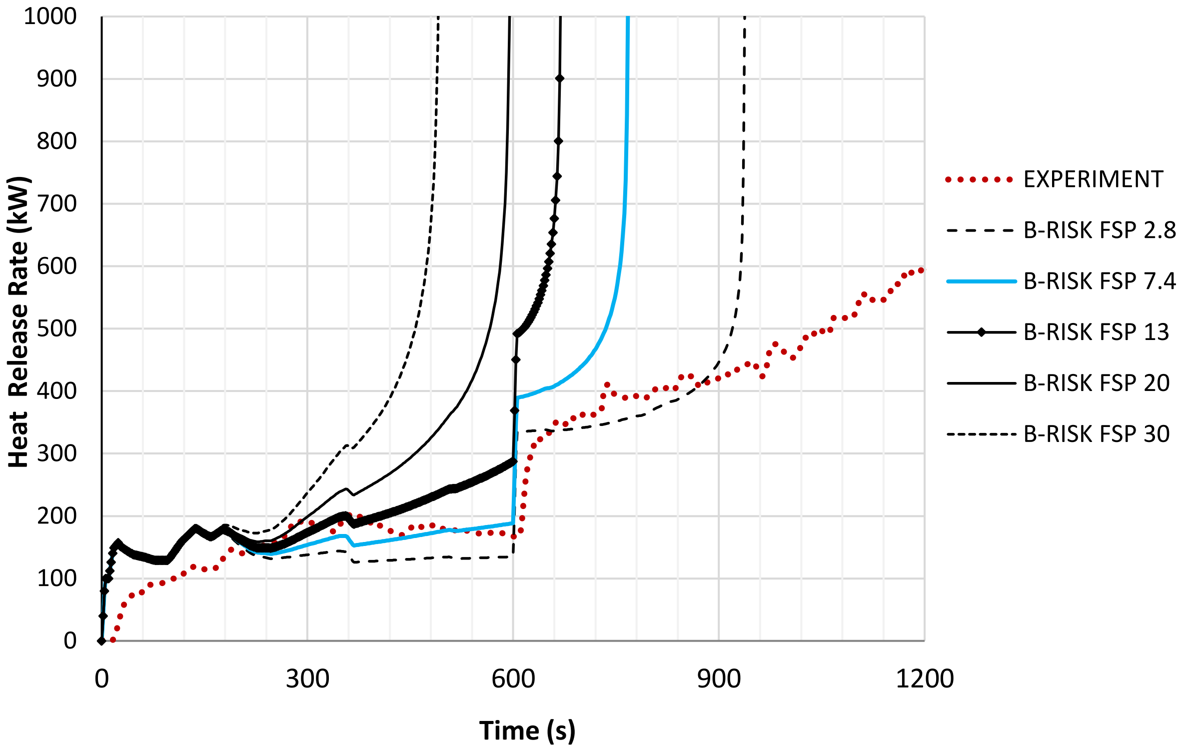


Figure 7.17: Modelled heat release rates for Experiment 3 using various flame spread parameter (FSP) values

7.5.2 Minimum temperature for flame spread

The modelling is compared with three different $T_{s,min}$ values: 164 °C (Quintiere, 1998), 175 °C based on the findings of Lattimer (Lattimer, Hunt, Wright, & Usman, 2003) for 9.5 mm thick Douglas fir plywood and 200 °C as an upper minimum temperature for flame spread to test the limit of sensitivity. The simulations are generally not sensitive to variations in the minimum temperature for flame spread, with very little change in heat release rates such as in Experiment 5 (Figure 7.19). However, Experiment 3 shows a significant increase in the time to flashover when $T_{s,min}$ is increased to 200 °C and underestimates the heat release rate compared to the experiment over the first 10 min (Figure 7.18).

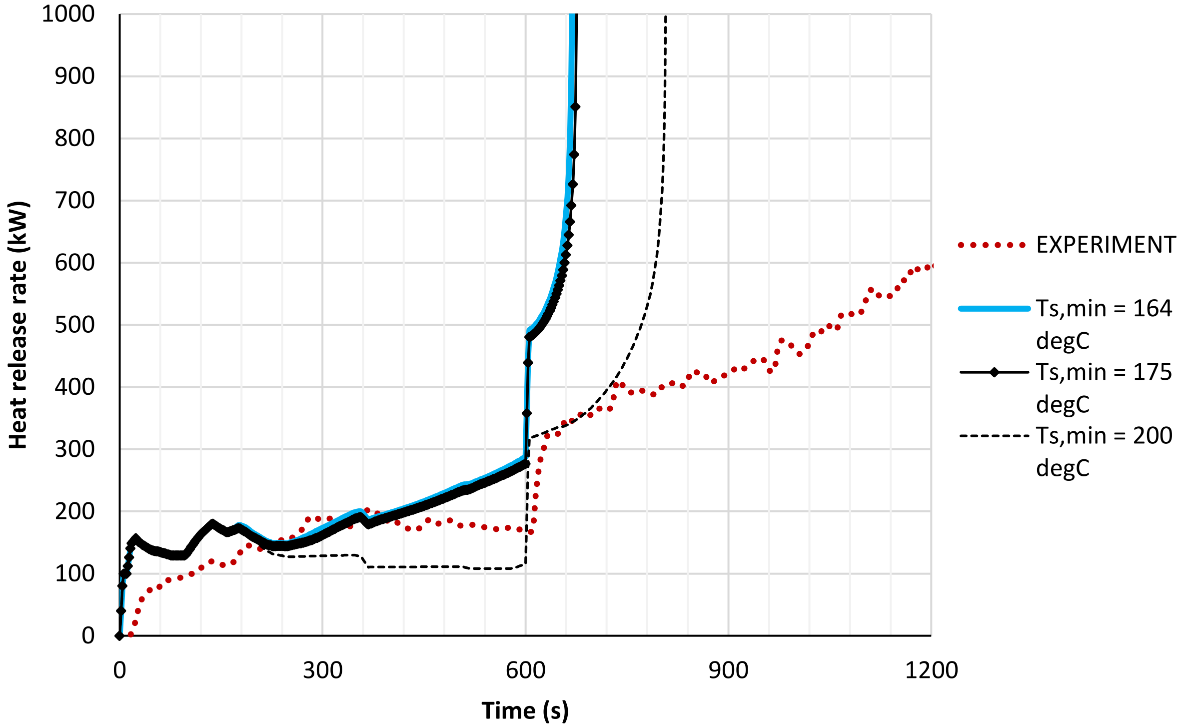


Figure 7.18: Modelled heat release rates for Experiment 3 using increasing minimum temperatures for flame spread ($T_{s,min}$)

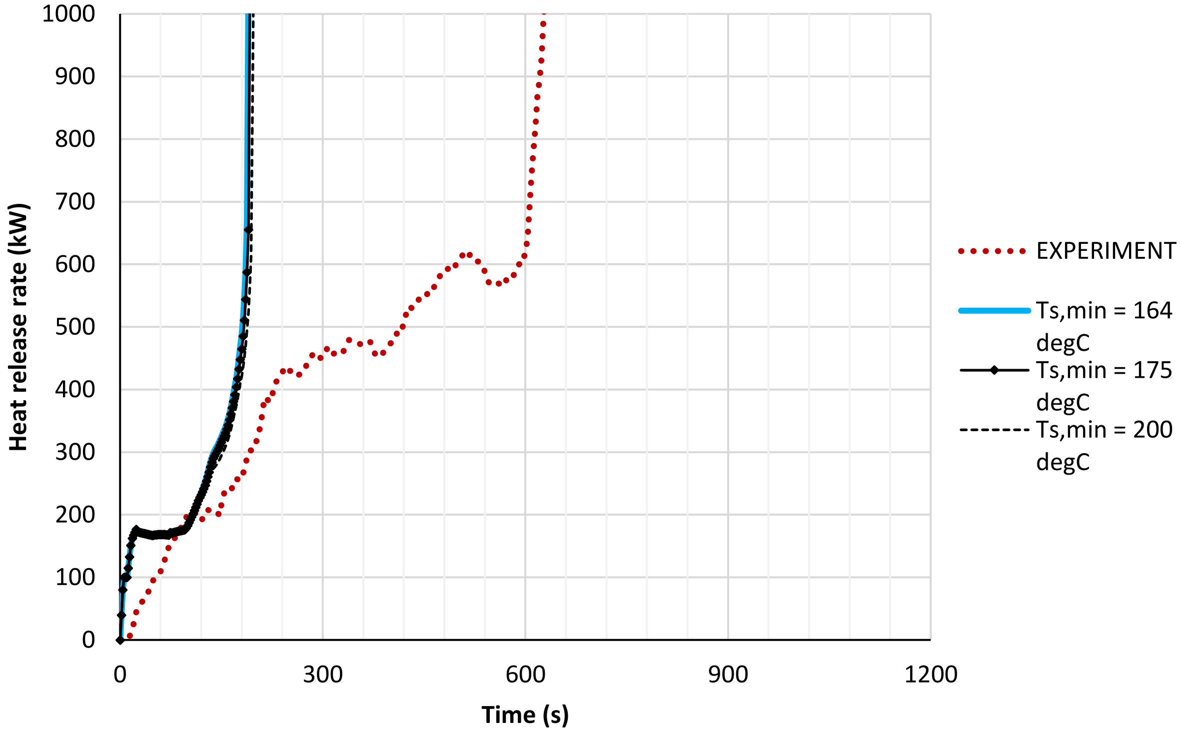


Figure 7.19: Modelled heat release rates for Experiment 5 using increasing minimum temperatures for flame spread ($T_{s,min}$)

7.5.3 Maximum flame spread rate

As described in Section 6.4, flame spread rates before flashover of 0 mm/s to 20 mm/s for lateral and downward spread were observed during the experiments. Upward flame spread, and the rate of flame spread within the ceiling jet, were observed to range from 8 mm/s to 25 mm/s prior to flashover. The initial modified B-RISK model limits the flame spread rate to 10,000 mm/s, once the lining material reaches its ignition temperature. This is an arbitrary maximum derived from earlier literature which states that once the ignition temperature of the lining is reached, the plywood is pyrolysed and the flame spread rate no longer applies, as the flames are premixed and flame spread rates are very rapid. However, there is very little difference in heat release rate results when this maximum in changed from 10,000 mm/s to 100 mm/s.

An additional modification to B-RISK has been made wherein the maximum flame spread rate (both lateral and upward) are limited.

Figure 7.20 to Figure 7.25 show that when modelled with a peak flame spread rate of 10 mm/s, which is within the observed range, heat release rates showed the best initial agreement with the experimental curves, but did not achieve flashover. A modelled maximum flame spread rate of 50 mm/s gives the best agreement with the experimental results, although runaway heat release rate eventually occurred in all the simulations.

7.5.4 Plume Entrainment

When calculating the rate of air entrainment into the plume, the energy from the burning linings (below the layer interface) is assumed to come from a single plume in the corner of the room. B-RISK uses an entrainment correlation for a corner fire. The entrainment is therefore likely to be underestimated due to the burning wall as this is a burning surface with a larger perimeter and different plume characteristics than a corner plume. The effect of the corner plume assumption is seen in Section 7.4.2 where the upper layer gas temperature is consistently over-predicted in the simulations compared to the experimental results.

The wall surface temperatures will also be over-predicted, as this is derived from heat transfer from the upper layer. This means that the rate of lateral flame spread rate which is found using equation [4.3] with T_s replaced by the wall surface temperature, will also be over-estimated. The models were repeated using the "disturbed plume," to describe the smoke plume rather than the undisturbed plume normally used for corner and centrally located fires. While the disturbed plume function is normally reserved for spill plumes, this command has the effect of doubling the rate of entrainment into the plume. Increasing the entrainment rate consistently improves the agreement between experiment and simulations as shown in Figure 7.20 to Figure 7.25. However, Figure 7.21 shows that for Experiment 3, increasing the entrainment causes the heat release rate to be underestimated during the first 600 s.

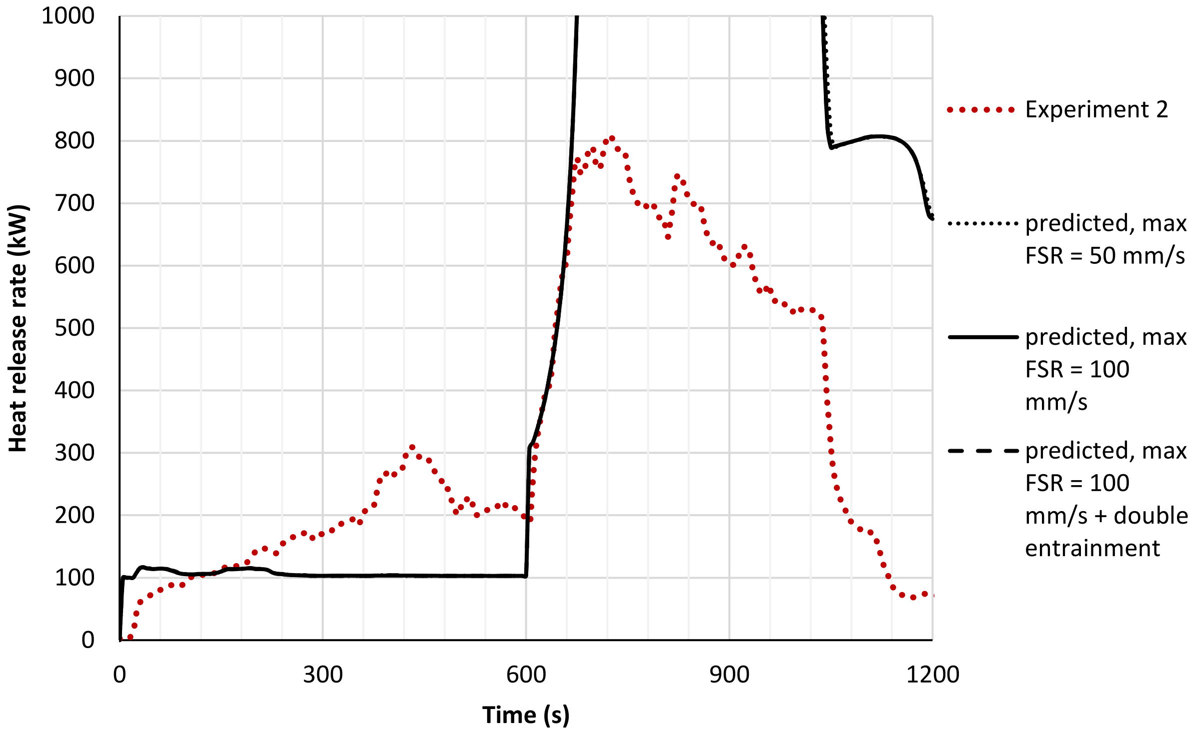


Figure 7.20: Modelled heat release rate using varied maximum flame spread rates and entrainment rates for Experiment 2

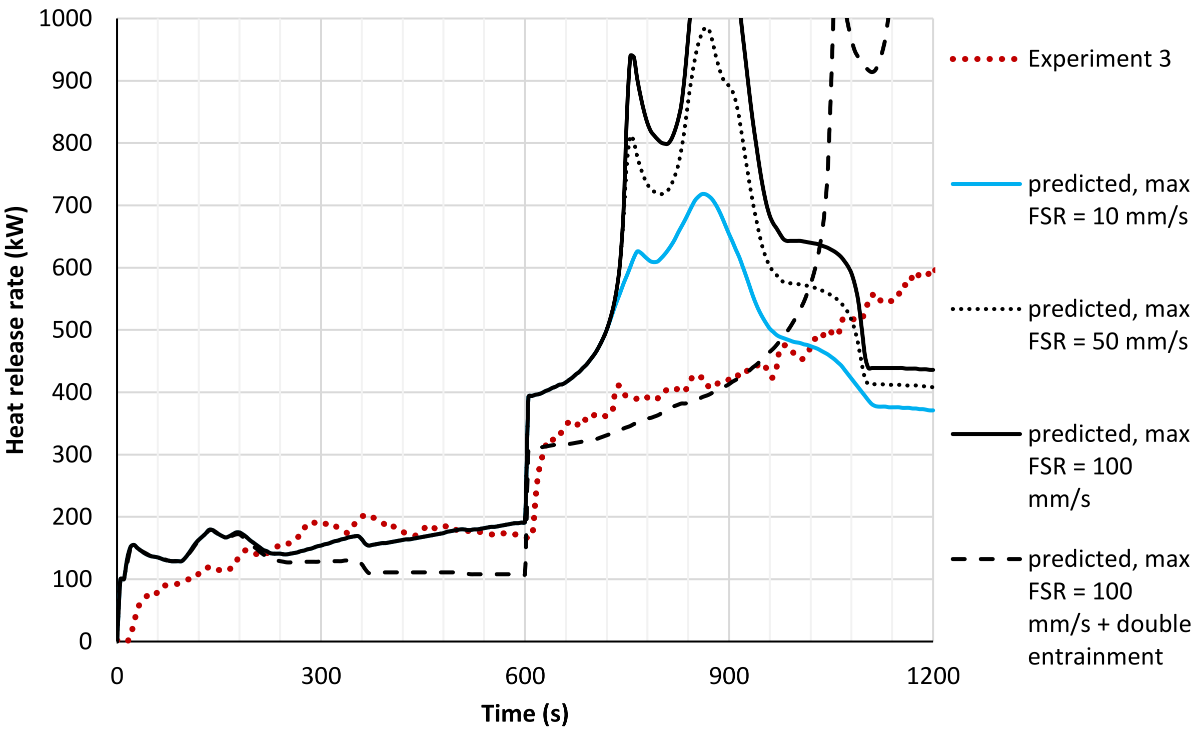


Figure 7.21 Modelled heat release rate using varied maximum flame spread rates and entrainment rates for Experiment 3

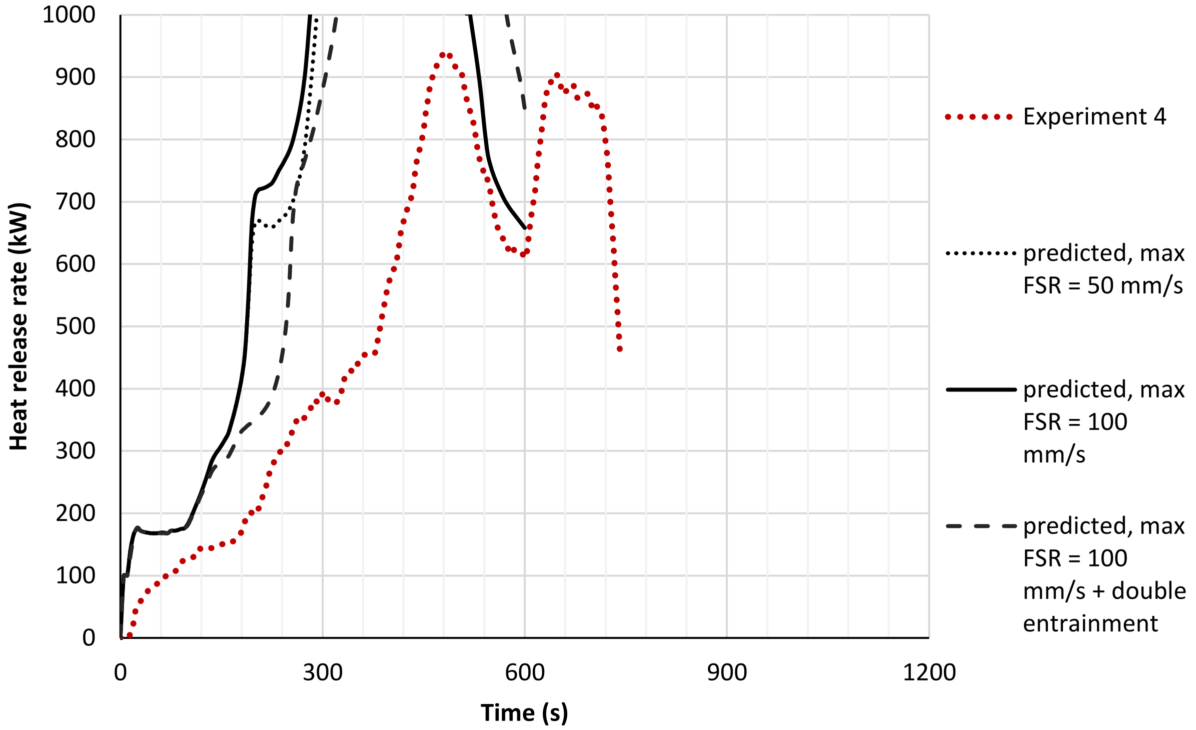


Figure 7.22: Modelled heat release rate using varied maximum flame spread rates and entrainment rates for Experiment 4

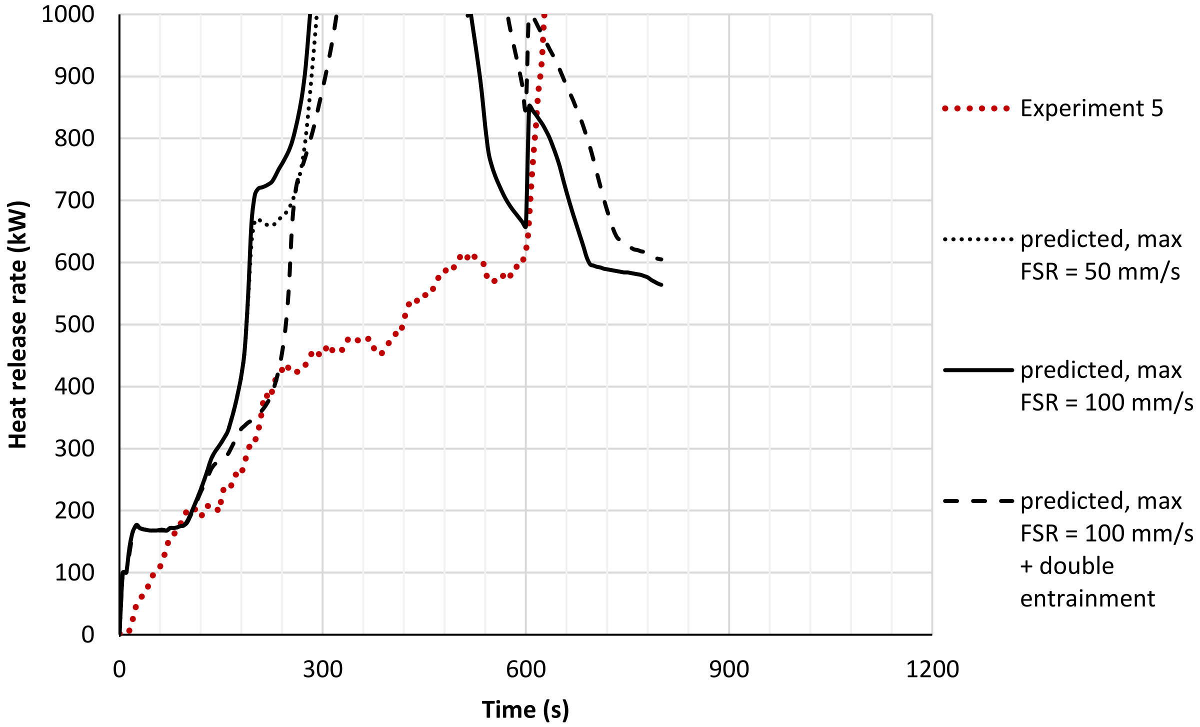


Figure 7.23: Modelled heat release rate using varied maximum flame spread rates and entrainment rates for Experiment 5

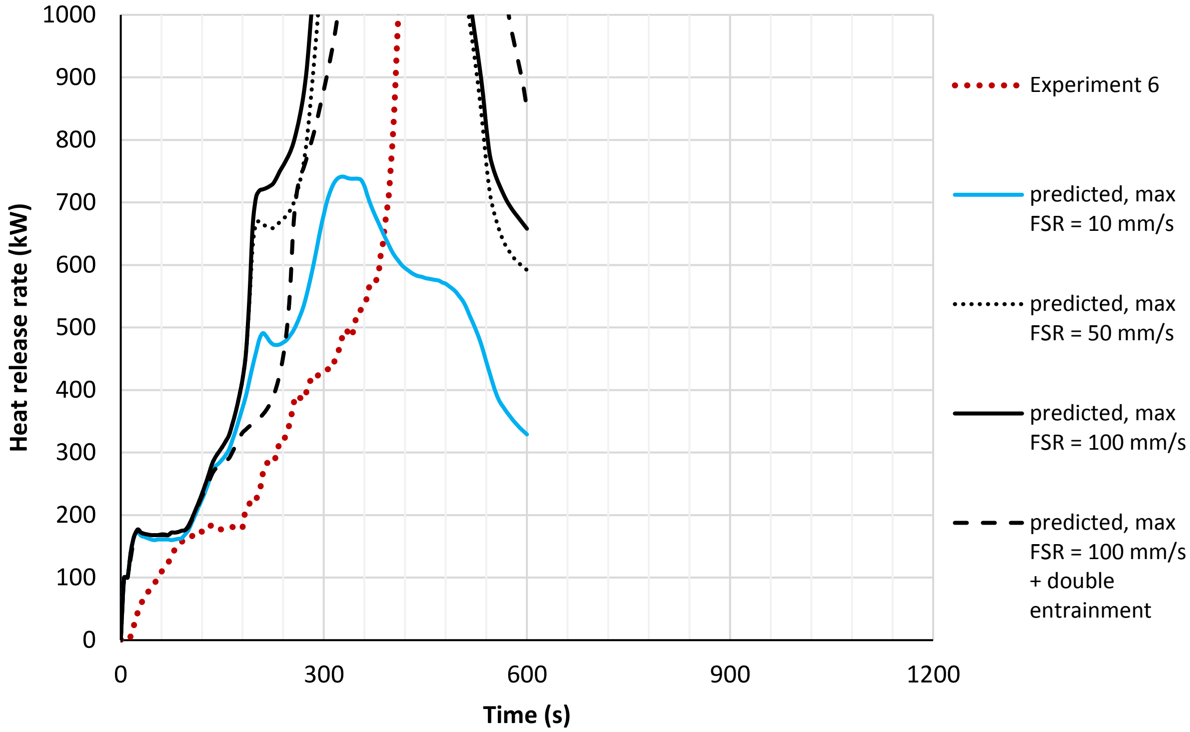


Figure 7.24: Modelled heat release rate using varied maximum flame spread rates and entrainment rates for Experiment 6

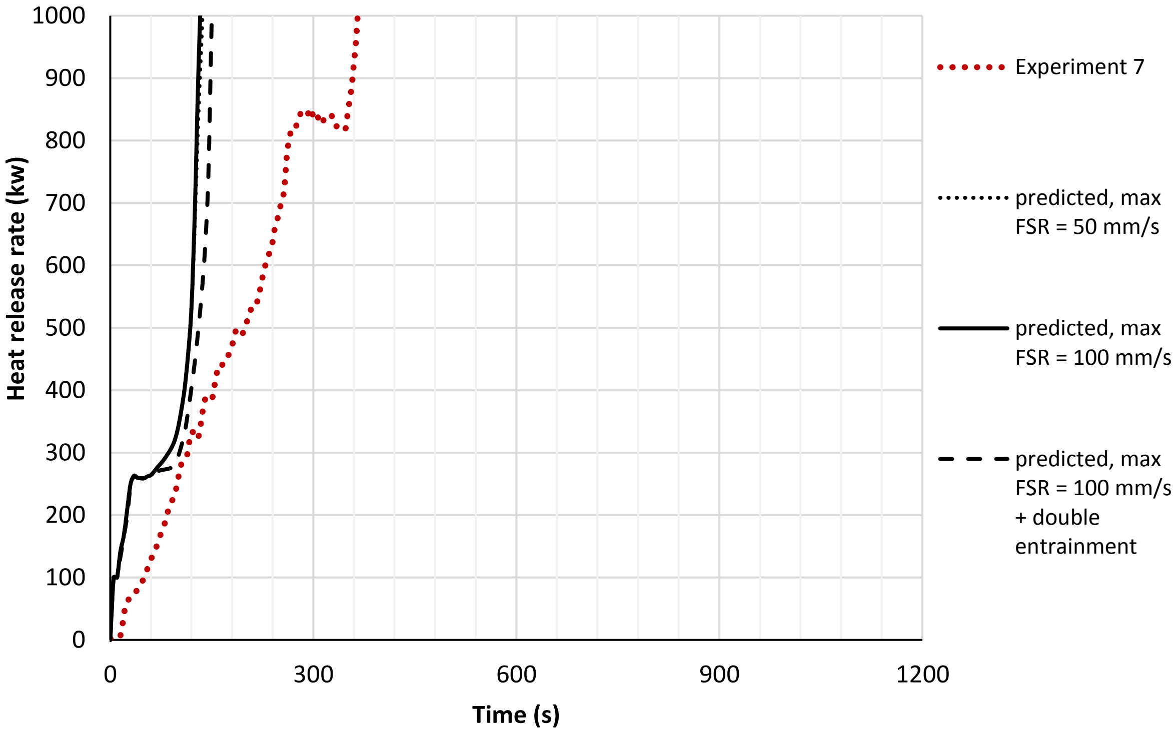


Figure 7.25: Modelled heat release rate using varied maximum flame spread rates and entrainment rates for Experiment 7

8. Summary

8.1 Limitations

The results of the experiments and the model comparisons discussed in this thesis are specific to the experimental work undertaken as part of this thesis. The results are therefore limited to the seven tests undertaken at the BRANZ testing facility.

There are a number of simplifications inherent in the ISO 9705 test when used for evaluating the fire performance of surface linings. These include that the room is smaller than many spaces in real buildings and does not include room contents which would contribute to overall fire load. Furthermore, the burner location was fixed in the rear corner of the enclosure, so conclusions cannot confidently made as to the effect of high level ignition sources such as on a shelf or in a ceiling on flame spread on rooms with partial combustible linings.

The lining that was evaluated was 7 mm thick untreated New Zealand pine plywood. It is difficult to accurately predict based on this work how timber of various thickness or species may have performed in the partially linied ISO 9705 experiments. Similarly the effect of varnish, sealants and/or paints on fire performance of the timber lining was not included in the suite of experiments, therefore the conclusions are limited in their application to varnished or painted timber linings.

Furthermore, not all inputs to the B-RISK model characterising the plywood in this work were found experimentally; the flame spread parameter and minimum temperature for flame spread, for example, were taken from the literature. The model was somewhat sensitive to these values, and any discrepancy between the literary values and the actual plywood values (had these been tested) may have negatively affected the accuracy of the B-RISK model.

Each configuration was tested only once as there was significant set up time and expense to each test. It was therefore difficult to ascertain whether the results of each experiment were characteristic of the lining configuration question, or represented an exceptionally rapid or slow fire development for that lining layout. This was particularly relevant in Experiments 2 and 4, which came "close" to the arbitrary 1 MW flashover, with peak heat release rates of 809 kW and 941 kW respectively. In repeated tests, it is possible that, due to the inherent variability in fires, some repeated tests would have achieved flashover and impacted the ranking of severity of the fire performance of these configurations, as well as its comparison with the B-RISK model.

8.2 Conclusions

Six experiments using the protocols of ISO 9705 have been undertaken wherein small enclosures partially lined with 7 mm thick plywood have been exposed to a gas burner ignition source. An additional experiment of a fully lined room of the same surface lining has also been undertaken to facilitate comparison.

It was observed that there is considerable variation in performance (measured in terms of flame spread as well as maximum rate of heat release) in those partially lined configurations, even with the same total area of plywood. The height of the plywood lining above the floor (where the ignition source was located), the proportion of timber in the space, and the provision of a combustible 'path' from ignition source to upper linings have been identified as factors affecting the time to flashover in the room. It is proposed that some configurations may have achieved greater rate of heat release values if thicker plywood had been used as the total burn out of lining material in some areas seemed to limit flame spread and the peak rate of heat release obtained.

Finally it was shown that, despite concessions in some jurisdictions for low level timber linings, the amount of combustible linings located at high levels is not the only contributing factor for flashover. In fact, the ceiling only, and upper wall only tests did not flashover, despite having the majority of the fuel load within, or close to, the upper layer. This finding was attributed to the fact that the burner flames did not reach the ceiling until the burner was increased to 300 kW. This outcome shows that fire performance of linings does not solely relate to the proximity of linings to the hot upper layer – the location of the ignition source, the size/strength of the burner flames and their incidence on the combustible lining as well as the presence of timber at low levels to form a path for flames to spread upwards are all factors which must be considered when attempting to predict the fire performance of partially lined enclosures.

The flame spread model described in this work has shown some promise in predicting the rate of heat release in the ISO 9705 enclosure where the room is partially lined with 7 mm thick plywood, particularly when there is a large amount of lining positioned close to the burner. B-RISK is less accurate in its predictions for partially lined enclosures with lesser amounts of material. The B-RISK model been shown to consistently predict flashover earlier than was observed during experiments which is acceptable from an engineering perspective.

B-RISK demonstrated a tendency to over-predict the upper layer gas temperature when wall linings were burning. This was attributed to underestimating the rate of entrainment into the fire plume. It was likely this also resulted in higher wall surface temperatures and faster predicted lateral flame spread and fire growth. These dependencies should be further investigated.

The sensitivity of the model to the minimum temperature for flame spread and the flame spread parameter has been investigated and generally found to be not very important in comparison to changes in plume entrainment. The only case where this was not observed was when the plywood was located only on the lower half of the walls. In that case, the surface linings are cooler and the effects of the flame spread parameter and minimum temperature for flame spread became relatively more important when calculating the heat release rate. The model is sensitive to the maximum flame spread rates, and agreement between the modelled and observed heat release rates was better at rates of 5 cm/s or below. However, the most important parameter identified during sensitivity analysis, was the rate of entrainment into the plume. Increased entrainment, even with greater maximum flame spread rates, appeared to reduce the upper layer temperature and delay flashover in the model prediction.

8.3 Further work

This study was intended to investigate how reducing the extent of timber linings in a space can affect the severity of a fire. It was successful in identifying some aspects of lining layout which affect fire development. However, the results are limited to the configurations that were tested, and are only applicable without further analysis to enclosures that are similar in size and proportion to the ISO 9705 room. It would therefore be valuable to conduct further full-scale experiments using combustible linings in more configurations and in rooms of different sizes to the ISO 9705 to identify trends in fire development and further evaluate the effects of the relative location of wall linings of varying combustibility on fire development.

Similarly, the promising agreement of B-RISK modelling with the experimental results indicated that it is feasible to use the B-RISK zone model to simulate fires in partially lined enclosures with reasonable accuracy, although the simulated times to flashover were consistently conservative. Even greater accuracy and less conservative results for upper layer temperature and heat release rates than shown in this work would ultimately provide designers and engineers with more lining design options, and greater confidence in the existing combustible lining concessions included in design legislation. The modified B-RISK flame spread model would benefit from increased analysis of flame spread in enclosures at an incremental level to inform the model, as well as larger scale testing for comparison with simulation results. In particular, further research into peak flame spread rates over surfaces in room fires, as well as the entrainment of air into fires over burning surfaces, such as walls and ceilings rather than corner or central plumes would be valuable.

Furthermore, it would be useful to fire engineers if this tool could be shown to provide accurate results for larger spaces, and other combustible lining configurations. This could be achieved by further testing in different enclosure sizes for comparison with B-RISK.

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Appendix A: Permitted Surface Linings Classification by Jurisdiction and Occupancy

W = wall lining NS = not sprinklered [shaded] = class which permits bare timber FA = Floor area p = persons

C = ceiling lining S = sprinklered N/A means that those occupancies are not permitted to be unsprinklered

Healthcare refers to those occupancies where care or treatment is provided and occupants may not be able to egress unaided.
Detention has not been included as many jurisdictions (Australia, England, U.S.) require performance based design for these areas.

			Assembly		Education		Healthcare		Accommodation		Business		Mercantile	
			W	C	W	C	W	C	W	C	W	C	W	C
Exitways	NZ	S	2	2	2	2	2	2	2	2	2	2	2	2
		NS	1	1	1	1	1	1	1	1	1	1	1	1
	AUS	S	1	1	1	1	1	1	1	1	1	1	1	1
		NS	1	1	1	1	1	1	1	1	1	1	1	1
	ENG	S	0	0	0	0	0	0	0	0	0	0	0	0
		NS	0	0	0	0	0	0	0	0	0	0	0	0
	CAN	S	25	25	25	25	25	25	25	25	25	25	25	25
		NS	25	25	25	25	25	25	25	25	25	25	25	25
	U.S.	S	A	A	B	B	A	A	A	A	B	B	B	B
		NS	A	A	A	A	N/A	N/A	N/A	N/A	B	B	B/C	B/C
Corridors	NZ	S	3	3	3	3	2	2	2	2	3	3	3	2
		NS	3	3	3	3	N/A	N/A	2	2	3	3	2	2
	AUS	S	3	3	3	3	2	2	3	3	3	3	3	3
		NS	2	2	2	2	1	1	2	2	2	2	2	2

			Assembly		Education		Healthcare		Accommodation		Business		Mercantile	
			W	C	W	C	W	C	W	C	W	C	W	C
	ENG	S	1	1	1	1	1	1	1	1	1	1	1	1
		NS	1	1	1	1	1	1	1	1	1	1	1	1
	CAN	S	150	150	150	150	150	150	150	150	150	150	150	150
		NS	75	25	75	25	75	25	75	25	75	25	75	25
	U.S.	S	C	C	C	C	A	A	B	B	C	C	B/C	B/C
		NS	B	B	B	B	N/A	N/A	N/A	N/A	B	B	B/C	B/C
Other Spaces	NZ	S	3	Crowd area: 2 Other: 3	3	Crowd area: 2 Other: 3	3	Sleep area: 2 Other: 3	3	Sleep area: 2 Other: 3	3	3	3	3
		NS	Crowd areas: 2 Other:3	Crowd area: 2 Other:3	Crowd area: 2 Other:3	Crowd area: 2 Other:3	N/A	N/A	Sleep area: 2 Other: 3	Sleep area: 2 Other: 3	3	3	3	3
	AUS	S	3	3	3	3	3	3	3	3	3	3	3	3
		NS	3	3	3 Classroom: 2	3 Classroom: 2	3 Patient care: 2	3 Patient care: 2	3	3	3	3 Low ceiling space: 2	3	3 Low ceiling space: 2
	ENG	S	Floor Area > 30 m^2: 1 Floor Area < 30 m^2: 3				Floor Area > 4 m^2: 1 Floor Area < 4 m^2: 3				Floor Area > 30 m^2: 1 Floor Area < 30 m^2: 3			
		NS	Floor Area > 30 m^2: 1 Floor Area < 30 m^2: 3				Floor Area > 4 m^2: 1 Floor Area < 4 m^2: 3				Floor Area > 30 m^2: 1 Floor Area < 30 m^2: 3			
	CAN	S	150	150	150	150	150	150	150	150	150	150	150	150
		NS	75	75	150	150	75	75	150	150	150	150	150	150
	U.S.	S	< 300p= B >300p= C	< 300p= B >300p= C	A	A	A	A	C	C	B	C	C	B,C
		NS	300pp= A >300p = B	300p= A >300p = B	B	B	N/A	N/A	N/A	N/A	C	C	C	B,C